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Photograph by Harsha Vadlamani

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SCIENTIFIC AMERICAN
The New Science of Human Metabolism

ON THE COVER

Until recently, scientists had little hard data about how the human body burns calories from food. New research provides key insights, overturning received wisdom about how metabolism changes over the course of a lifetime. Related work has illuminated how we evolved to meet our considerable energy needs. **Illustration by Eva Vázquez.**

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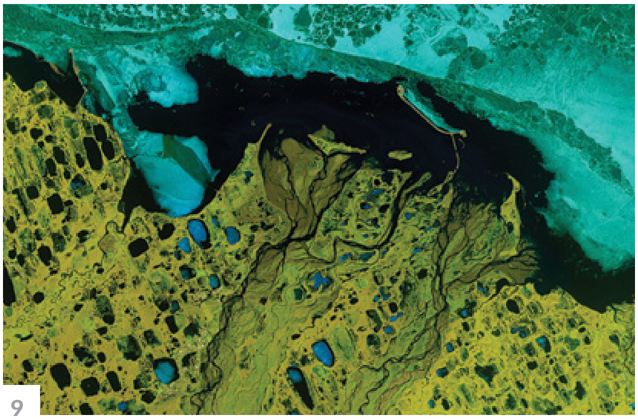
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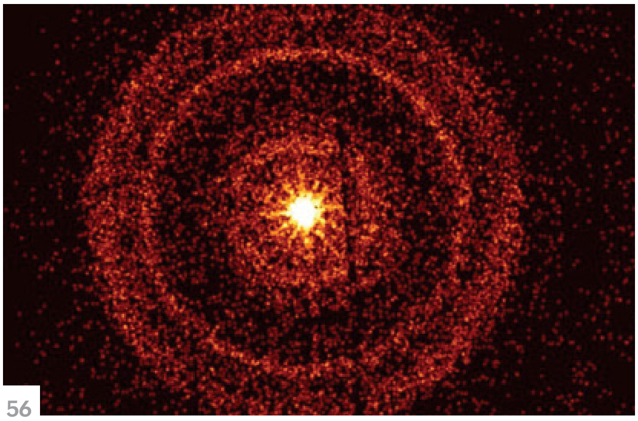
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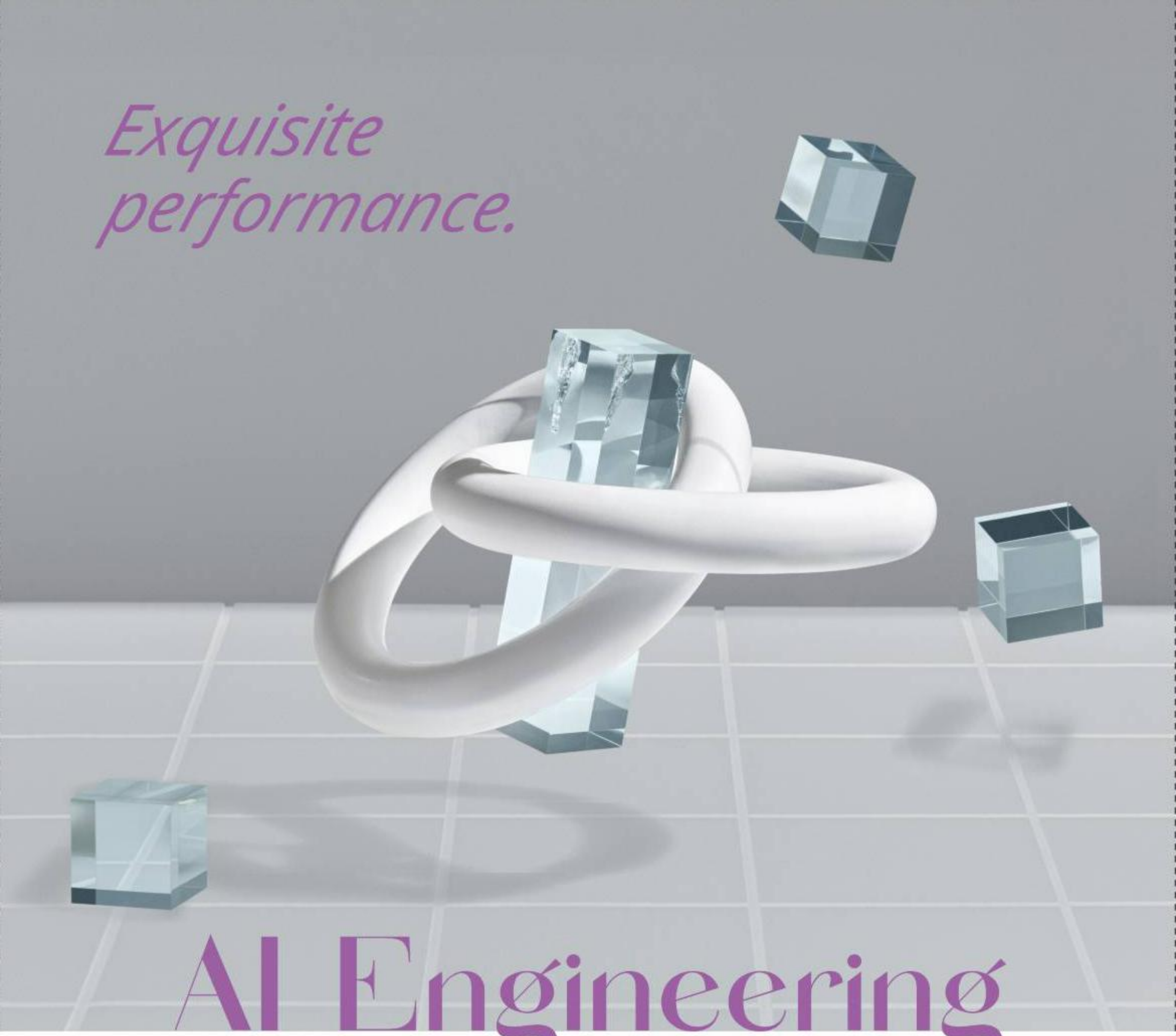

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FROM THE EDITOR

Laura Helmuth is editor in chief of *Scientific American.* Follow her on Twitter @laurahelmuth

Burning Energy

A lot of people have made a lot of money spreading myths and misinformation about metabolism. Nutritional supplement ads, diet books and pseudoscientific health websites claim they can help you boost your metabolism. Sometimes part of the pitch is that metabolism, which is just how your body uses energy, slows down in middle age or that women have a slower metabolism than men. The myths are persistent in part because the diet and supplement industries are so profitable and so poorly regulated. But misinformation also sneaks in because metabolism is really hard to study. Now, as evolutionary anthropologist Herman Pontzer writes in our cover story, starting on page 24, scientists have figured out that much of what people think they know about metabolism isn't true. It doesn't slow down in middle age, for starters, and there aren't sex differences. He and his colleagues have also traced the evolution of human metabolism—we use a good deal more energy than other great apes—and provide even more evidence that what makes humans human is cooperation.

Astronomers recently witnessed the synthesis of heavy elements for the first time. It all started when a distant star exploded and its core turned into a dense neutron star. Then its partner in a binary star system did the same. The two neutron stars spiraled into each other in a ripping crash that spilled neutrons into atoms of iron or other lighter elements. The spectacular collision set off gravitational waves that traveled 130 million light-years to Earth, accompanied by light with a spectrum that showed the presence of the heavy element strontium, the first direct observation of a heavy element being forged. Nuclear astrophysicist Sanjana Curtis explains on page 30 how the heaviest elements are made and why it's no exaggeration to say that we are made of stardust.

One of our features in this issue is about death and grief and the extinction of languages and cultural traditions … but trust me, it's a pleasure to read. On page 38, anthropologist Piers Vitebsky shares his life's work among the Sora Indigenous people, who live in highlands of eastern India. He started documenting their language and religious practices in the 1970s and has witnessed massive cultural changes as young Sora convert to more dominant religions. The traditional mourning rituals he describes are among the most elaborate and psychologically astute rites any religion has come up with. He uses the term "theodiversity" to describe what's being lost as people abandon long-held beliefs about the origins of the world and the nature of life and death.

The 2022 Nobel Prize in Physics went to three scientists who helped to prove that the universe is not locally real. Really. Their work in quantum physics has advanced quantum computing and expanded human knowledge, and it is undoubtedly very important, but it's also kind of unnerving. Things aren't "real" unless someone observes them. "Local" refers to the idea that things can be influenced only by their environment, but it turns out that they can be influenced in bizarre and extremely long-distance ways. Science journalist Daniel Garisto chronicles on page 48 how quantum physics went from crackpottery to a hot field and spells out why quantum entanglement could be both mind-bending and useful. We hope you enjoy what he calls "one of the more unsettling discoveries in the past half a century." SA

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INSIDE
HOW WORMHOLES RESOLVE A PARADOX
THE EDGE OF SPACE AND TIME
OUR BLACK HOLE REVEALED

September 2022

HORIZONTAL VIEWS

In "A Tale of Two Horizons," Edgar Shaghoulian provides an intriguing alternative view of black holes and our entire cosmos as well. Especially of interest is his statement that "we must find a way to look at the cosmic horizon from the outside." Yet that assumes there is an outside. Moreover, if one does exist, what is outside of that?

I am afraid we anthropomorphize the universe when attempting to describe it in familiar terms such as in the holographic principle. Our observations require an observer—us. We use our senses and employ instruments whose measurements must ultimately also depend on our interpretations. Perhaps it is human hubris, which knows no bounds. Our species evolved in order to survive on Earth, not to understand the cosmos. Perhaps the universe is not only stranger than we understand; it may be stranger than we *can* understand.

Barry Maletzky *Portland, Ore.*

SHAGHOULIAN REPLIES: I am a perennial optimist: our ability to understand quantum mechanics and Einstein's general theory of relativity far beyond what is needed evolutionarily gives me hope that we will understand the cosmos as well. Whether there is really an "outside" of the cosmic horizon is a tricky question. The equations suggest that it's there. But historically, it has sometimes been argued to be metaphysical because measuring the existence of something requires interacting with it, and by definition, we cannot receive signals from beyond our event horizon. This is why some of us find the potential nonlocal connections between the two sides of an event horizon so intriguing: we will be able to access what was once thought of as forever lost.

> **"Perhaps the universe is not only stranger than we understand; it may be stranger than we *can* understand."**
>
> BARRY MALETZKY *PORTLAND, ORE.*

PRESERVING INFORMATION

Thank you for "Paradox Resolved," George Musser's article on the black hole information paradox. I have questions that look not forward toward the principle used to crack that paradox but rather backward: As Musser describes, the laws of physics require that the information needed to reverse anything that happens in the physical world is always preserved. Does this information preservation principle imply that all information was already in existence in the big bang singularity? And if information has only been created after the big bang, does such an information increase then reduce entropy?

G. Rhine *Philadelphia*

MUSSER REPLIES: This is an extremely perceptive question. Information preservation is a synonym for determinism. All that happens now was set at the big bang—or indeed at any other moment (there is no reason to assume it must be in the past). This comes with the important caveat that the information we're talking about is the global quantum state, which evolves according to the Schrödinger equation. But any subsystem of the universe will see information generation or destruction.

THE TURING TEST LIVES

In "AI Writes about Itself," Almira Osmanovic Thunström describes how she and her colleagues instructed the artificial-intelligence algorithm GPT-3 to write a scientific paper with itself as the subject. As I read the article, it came back to my mind that, in the 1980s, a colleague of mine wrote a toy program: with half a dozen randomly chosen words as input, it produced a text that was syntactically correct. He had named the program "bullshit generator."

Pier Giorgio Innocenti
Grand-Saconnex, Switzerland

I have been reading *Scientific American* and other noted science magazines for decades, and Thunström's article about GPT-3 writing an academic paper about itself was among the most fascinating because it raises new issues that many of us have never considered before. Certainly the ethical issue of nonsentient authorship is the most absorbing. And of course, the impact on who gets credit for what will occupy the minds of some scientists because academia is so competitive.

Use of this algorithm might begin to change everything about how we value creators of ideas, not just papers. I am also impressed with how GPT-3's use of language was so human-sounding. It seems like it could pass the Turing test.

Robert Walty *Stephens City, Va.*

NOVEL EXPERIENCE

Thanks for including works of fiction in your book reviews. I see the September column has an appreciation of a reissued classic by Octavia E. Butler in "A Time Traveler's Legacy" [Reviews]. But I have noticed fairly regular fiction reviews over the past year or so—something I don't recall in many issues over the past 50-odd years. (Is my memory playing tricks on me, or did *Scientific American* include a review of Thomas Pynchon's *Gravity's Rainbow* in 1973?) As an old English major with a curious layperson's interest in science, I appreciate this broadening of the kinds of books you recommend to your readers.

James Yarnall *Pisgah Forest, N.C.*

THE EDITORS REPLY: Yarnall's memory is sound: our longtime book review editor Philip Morrison wrote about Gravity's Rainbow in our October 1973 issue.

ENERGY INFRASTRUCTURE

It is misleading for the Editors to say the time is right for "Electrifying Everything"

[Science Agenda; July 2022]. Currently our electricity sources are only fractionally renewable. A higher priority is reducing the carbon content of the grid while improving its reliability.

As we move to more renewables, we are going to need technology for storing energy. Batteries are great for some things, but nature stores energy in chemical form. We have biofuels and hydrogen now, and technology has to advance only a little for making renewable methane—which could be used perfectly in existing natural gas infrastructure and serve as a bridge to an actual all-electric future.

Max Sherman *Retired senior scientist, Lawrence Berkeley National Laboratory*

CONTINENTAL COINCIDENCE

I noticed an artful and odd coincidence in "Dynamic Seas," by Mark Fischetti, Kelly J. Benoit-Bird, Skye Morét and Jen Christiansen [Discoveries from the Deep; August 2022]: At the center of the "Conveyor Belt" infographic is Antarctica. The continent is surrounded by all the world's oceans, with red and blue lines showing warm and cold major ocean currents. The layout of the world's oceans resembles a surprising replica of the shape of Antarctica itself.

Duncan Clark *via e-mail*

ERRATA

"Protecting Kids' Mental Health," by Mitch Prinstein and Kathleen A. Ethier [Forum], should have said that in 2019 about one in five high school students surveyed seriously considered suicide and that about one in 11 attempted suicide, not that about one in five seriously considered or attempted suicide.

"Testing Nukes," by Adam Mann and Alastair Philip Wiper [October 2022], should have said that "some" of the $15 billion a year the nation spends to research and test nuclear material goes to the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, not "much" of that amount. The NIF's current yearly budget is $349 million.

"Saving the Night Sky," by Joshua Sokol [October 2022], should have described the blue-white light fixtures used in an experiment in New York City housing developments starting in 2016 as left on from sunset to sunrise, not sunrise to sunset.

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What Science May Bring in 2023

We share what we are watching in the new year

By the Editors

For the editors at *Scientific American,* a new year is a chance to look ahead and predict what might unfold in the world of science and health. In 2022 we covered both inspiring and disturbing news—exquisite images from space telescopes, massively reduced reproductive rights in the U.S., efforts to dismantle environmental regulation, a war that laid bare our energy co-dependencies, a Nobel Prize for our Neandertal ancestry, and much more. Here's some of what we're paying attention to as 2023 arrives.

THE UNIVERSE

Massive satellite constellations are cluttering the night sky, two crewed space stations are operational, and nations are fielding new military capabilities in orbit. Governments in 2023 may see Earth's orbital regions as in urgent need of stronger international protections.

If the first orbital flight of SpaceX's Starship vehicle is successful, it could usher in a new era of exploration, space science and commerce because it will offer a less expensive way of getting cargo and crews off Earth. We also think 2023 will advance the search for life beyond Earth, whether the James Webb Space Telescope tells us about biosignatures on a distant exoplanet or we discover fossils in the rocks of Mars's Jezero Crater, where NASA's Perseverance rover is currently gathering samples.

CLIMATE ACTION

We still use a tremendous amount of fossil fuels, and European leaders, facing high costs and possible shortages because of the Ukraine War, will have to make serious decisions about energy infrastructure. We'll be watching what they decide to build, particularly for renewable energy and transportation of fossil fuels, as well as what existing structures they keep online. The recently elected U.S. government could determine future climate-related financial support and regulation. Simultaneously, science is revealing how much death and damage climate change is causing. We are hopeful that this burgeoning evidence will convince more people worldwide that we have to act now.

It's very likely 2023 will be a big year for recovery after storms, floods, droughts and wildfires, magnified by the ongoing global climate emergency. Part of that recovery will require officials to make decisions on whether to rebuild and, if so, how to do it in a way that helps us withstand climate change and avoid entrenching inequities. One question is whether adaptation mechanisms will be distorted by the powerful at the expense of fair and just action.

TECHNOLOGY

With Twitter in new hands and other social media sites downplaying their very real part in spreading misinformation, in 2023 we will need to modify how we as consumers of news decide what to believe and how we navigate the "infodemic." The federal government is starting to pay attention to privacy and antitrust issues, as well as the health consequences of the constant use of social media, all of which could dampen the tech sector. Tech firms that thrived during the pandemic are suffering, with major companies such as Meta, Stripe and Lyft laying people off. A tech slump could transpire.

HEALTH

Public interest in COVID and funds for researching it are decreasing. But people are still dying of the disease or are suffering from long COVID—which medical experts are just starting to investigate. The SARS-CoV-2 virus continues to evolve, and more vaccines and treatments are in the works. Outbreaks of other viruses, such as monkeypox, emphasize our need for better pandemic preparedness.

With abortion rights curtailed, we will keep covering the science behind the procedure, documenting how abortion bans or restrictions can harm pregnant people, especially those with limited access to health care. We will also continue to report on transgender health, the science of gender, and the effects of legislation on children and families seeking gender-affirming care.

MENTAL HEALTH

In the long search for new psychiatric drugs, psychedelics hold promise. The Food and Drug Administration may approve MDMA for post-traumatic stress disorder this year. Spravato (esketamine) was approved in 2019 as an antidepressant, and psilocybin is being tested to treat major depression. These chemicals are gaining legitimacy, but they aren't a panacea: three experts at the Johns Hopkins University School of Medicine recently warned these treatments suffer from a "hype bubble."

ANCIENT LIFE

DNA sequencing has revolutionized the study of ancient organisms, but genetic material deteriorates relatively quickly—the oldest DNA sequenced so far is about 1.2 million years old. Proteins survive longer than DNA molecules, and paleoproteomics has been gaining steam as a technique to help place extinct species in the tree of life. The coming year could be an important one for a research tool that recently helped illuminate the evolutionary history of a 23-million-year-old relative of the rhinoceros.

The sciences of our ancient world—paleontology and archaeology—as well as ecology and anthropology are undergoing a massive reckoning around the role of colonialism in scientific exploration. For one, racist species names are on notice. For another, a new generation of scientists is fighting against extractive practices that take specimens from developing nations to the Western world without consideration of local knowledge or without any benefit to the communities from which the items were taken.

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Deb Haaland is secretary of the U.S. Department of the Interior and a 35th-generation New Mexican.

Satellites Can Help Us Fight Climate Change

Landsat data will shape the Biden administration's climate change plans

By Deb Haaland

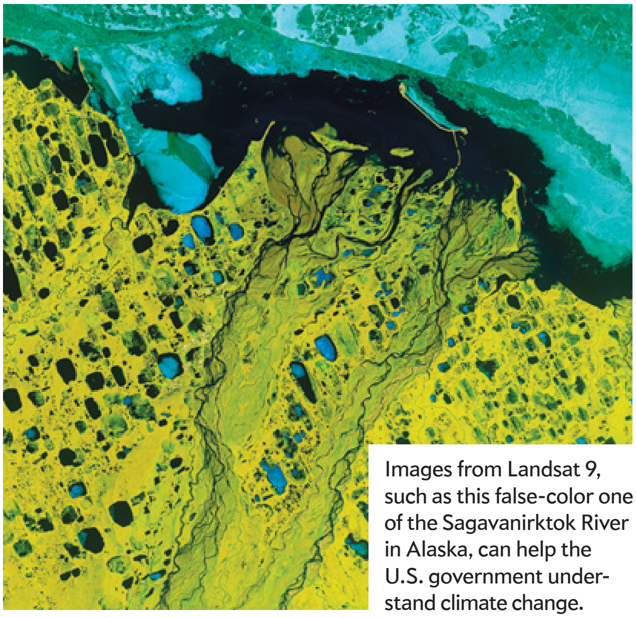
At the beginning of 2021, President Joe Biden exclaimed that "science is back" as we continued our efforts to address the COVID emergency. That phrase continues to ring true across the federal government. Science and its applications are being used at every agency—to identify public health challenges, build new transportation infrastructure, inform policy decisions and tackle the climate crisis.

At the Department of the Interior, using the best available science is a necessity for everything we do. Particularly noteworthy are the images of Earth from outer space that our scientists share with the public.

Recently the Interior Department's U.S. Geological Survey assumed operations of Landsat 9 from NASA, which built and launched it in 2021. This satellite is designed to monitor Earth's land, water and other natural resources. Landsat missions support environmental sustainability and climate resilience through higher-resolution satellite imaging. The Landsat program, which launched in July 1972, has helped us understand our planet and the changes that are occurring on it. That partnership has propelled research and observation forward through the launch of successive Landsat satellites, each replacing its predecessors and working in tandem with new capabilities and strengths.

I come from people who were among the first Earth observers, biologists and agriculturalists. Through generations of studying the cycles of the seasons and the flow of the waters and observing their environments, Indigenous peoples built complex communities to manage Earth's natural resources. They mapped the stars and watched the moon to understand when to plant and harvest. They practiced conservation as the first stewards of our lands and waters. The incredible possibilities that lie ahead for the Landsat program are an extension of my history and our history as a nation. What the satellites have shown us is that climate change's effects on the U.S. are undeniable.

I attended the historic launch of Landsat 9 in California. It was nothing short of amazing. I toured the mission control center and met a young scientist from the Navajo Nation living far away from home. She uses Landsat imaging to see her home from many miles away, and with such data, she enables her community to manage water resources in the face of a changing climate. This is the power and beauty of science at work.



Images from Landsat 9, such as this false-color one of the Sagavanirktok River in Alaska, can help the U.S. government understand climate change.

U.S. Geological Survey

All around the globe, scientists are using Landsat and other imagery to interpret what is happening on Earth today and to compare it with the 50 years' worth of data the Landsat program has collected.

But as exciting as that is, the forecast is grim. The images show the changes to our water resources, increased wildfire damage, amplified coral reef degradation, diminishing glaciers and ice shelves, and rapid tropical deforestation. As I travel across the U.S., I meet with communities who feel those changes.

Water allocations are at historic lows across the nation, creating an urgent need to minimize the effects of drought and develop long-term plans to facilitate conservation and economic growth. Sea-level rise is submerging coastal communities, displacing and endangering residents. Wildfire seasons are longer and longer, threatening homes and businesses. The stunning Landsat images can help us better support environmental sustainability, climate change resilience and economic growth—all while expanding an unparalleled record of Earth's changing landscapes.

This science-based program and those like it across federal agencies are powerful tools in our efforts to responsibly manage our resources. Their prioritization helps to demonstrate the Biden-Harris administration's commitment to lead with science. So, too, the resources provided through the president's Bipartisan Infrastructure Law and Inflation Reduction Act will be key to the development of longer-term sustainability measures as we respond to climate change, including building more resilient communities and protecting our natural environment.

Landsat NEXT is the upcoming mission we will develop with NASA to power better science and decision-making for the next 50 years. Science is indeed setting us on a path to a brighter future.

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ADVANCES

Researchers are investigating the bacterial communities within rare creatures, such as the kākāpō.

Stephen Belcher/Minden Pictures

INSIDE

- Cats pay attention to owners' special speech
- Light could guide tiny motors through the cell
- A human super-smeller inspires swab tests for Parkinson's disease
- Bacteria and fungi team up to crawl across human teeth

ECOLOGY

The Wild Microbiome

Rare animals' gut bacteria harbor survival secrets

New Zealand's critically endangered kākāpō, the world's heaviest parrot, is flightless and nocturnal, with fragrant moss-green feathers, an odd, whiskery face, up to a 90-year life span—and a gut microbiome made almost entirely of the bacterium *Escherichia coli.* Like humans, other animals carry trillions of bacteria, viruses, archaea and fungi in their digestive tracts, on their skin, and elsewhere: internal ecosystems that help them extract nutrients from food, fight pathogens and develop immunity. Now, as genetic sequencing becomes cheaper and more advanced, scientists are examining endangered animals' distinctive microbiomes, delivering insights that may help stave off extinctions.

Such research has revealed that kākāpō are bizarre inside as well as out, says University of Auckland microbial ecologist Annie West: "Their microbiome is pretty weird—like everything else about them." About 250 kākāpō remain on five remote, predator-free islands, where they are intensively managed by New Zealand wildlife officials. In 2019 government staff and volunteers collected fresh, brownish-green droppings and nest material from 67 growing chicks and sent the samples to West for DNA analysis.

E. coli is pervasive in the human digestive system, but it makes up just a small percentage of the bacteria that live there. Previous research had shown this microbe dominates adult kākāpō guts; the proportion varies considerably between individuals, and in some cases it makes up 99 percent of the entire microbiome. West and her colleagues' new study, reported in *Animal Microbiome,* found that shortly after a kākāpō hatches, *E. coli* already forms the microbial majority in its gut. And this dominance only increases as the chick grows up.

"It's very unusual. If you'd seen it in a human, you'd be worried," West says. It's not yet clear if it's bad for kākāpō, but a microbiome so homogeneous can be cause for concern because it may not carry out all the functions a species needs. "If you've lost diversity, you've potentially lost some functionality of the microbiome," West adds. The researchers also found that when they fed kākāpō chicks supplemental baby-parrot feed, a different bacterium took over their microbiome instead.

The kākāpō's simplified microbiome may be explained partly by the bird's extreme rarity. Other studies have shown that when animal populations shrink or become fragmented, some of the microbes they host are lost as well, says Lifeng Zhu, an ecologist at China's Nanjing Normal University, who was not involved in the new work. "As well as ecosystem and species diversity, we need to also conserve the microbiome diversity inside animals' bodies," Zhu says. Climate change, degraded habitats, contact with humans and time in captivity can all drastically alter an animal's microbiome, he explains—and when humans start intervening to save endangered species, we can have unintended effects on the miniature worlds within.

Zhu's own research has shown that giant pandas held in breeding facilities harbor completely different microbes than wild pandas do, mainly because they eat different food. When captive pandas are released, their microbiome must undergo a yearlong transformation, during which they are more likely to get sick. "We realized pandas need wildness of their gut microbiome," Zhu says, "not just wildness of their behavior."

Biologists are still cataloging which microbes live on and inside most endangered species, and how those communities change over time, says Flinders University marine biologist Elizabeth Dinsdale, who dives with sharks to collect samples of their skin microbes. Roughly 90 percent of the microorganisms she has found are new to science, and her team has identified different populations of whale sharks by their typical skin microbiomes.

The next big question is exactly what all these microorganisms do for their hosts. Whole-genome sequencing can provide hints by revealing the genes that make proteins for tasks such as digesting fiber, tolerating salinity and handling heavy metals. Culturing colonies in the laboratory, which helps to confirm a microorganism's role, is currently slow, expensive and difficult for many microbes. But emerging robotic technology promises to hasten the process, letting scientists observe how each microbe acts in concert with others.

A few researchers are already experimenting with microbiome engineering. For example, corals' mucus microbiomes are sensitive to temperature and pollution; overly warm seas can prompt corals to eject the symbiotic microalgae they rely on, causing bleaching. In Australia, Dinsdale says, scientists are testing whether they can climate-proof corals by treating them with "a sort of microbial elixir" of bacteria that are more accustomed to fluctuating temperatures. Other ecologists in Australia have shown it's possible to alter koala microbiomes with fecal transplants so the iconic marsupials can digest different species of eucalyptus.

In the U.S., Valerie J. McKenzie's lab at the University of Colorado Boulder is using probiotics to try to save boreal toads from chytrid fungal disease. Amphibians have a rich microbiome on their mucus-covered skin, which is where the devastating fungus *Batrachochytrium dendrobatidis* attacks. McKenzie's team identified a strongly antifungal bacterium that is naturally found in the endangered toads' Rocky Mountain habitat and in small quantities on their skin. The group showed in the lab that dousing toads in this probiotic microbe raised their ability to survive fungal infection by 40 percent.

Next, McKenzie and her colleagues captured young wild toads and put them up in spa-like "water hotels" to bathe in the probiotic for 24 hours before release. "You have to hit them in the perfect developmental time window" for the treatment to work, McKenzie says. When the treated toads were recaptured, they had less disease compared with controls.

West hopes her microbiome research will one day lead to similar treatments for kākāpō. At the very least, she says, now that the birds' typical gut makeup is known, routinely analyzing kākāpō poop could give conservation managers early warnings of disease. "The idea is that instead of taking invasive samples, you could use microbiome profiling to identify when an animal might be sick, even if you don't see any visible symptoms yet," West says. "And that starts to have big implications for conservation programs." —*Kate Evans*

ANIMAL BEHAVIOR

Kitty Talk

Cats recognize owners' speech

As any cat owner will tell you, talking to your cat is totally normal. And even though feline friends may seem indifferent to the adoring chatter, a new study in *Animal Cognition* suggests they really are listening.

Researchers in France subjected house cats to recordings of their owner or a stranger saying various phrases in cat- or human-directed speech. Much like baby talk, cat-directed speech is typically higher pitched and may have short, repetitive phrases. The team found that felines reacted distinctively to their owner speaking in cat-directed speech—but not to their owner speaking in adult tones or to a stranger using either adult- or cat-directed speech.

Previous research had shown similar findings in dogs, but much less is known when it comes to cats. "There are still some people who consider cats independent—that you cannot have a real relationship with cats," says lead study author Charlotte de Mouzon, an ethologist and cat behaviorist then at the University of Paris Nanterre. Some people might be embarrassed about using a special tone for cats, she says, but this research shows "people shouldn't be ashamed."

De Mouzon and her team recorded 16 cat owners uttering phrases such as "Do you want to play?" or "Do you want a treat?" in cat- and human-directed speech. The researchers then filmed each cat before, during and after playing it a series of recordings of its owner and other owners' speech. The researchers used software to rate the magnitude of the cats' reactions to a speech sound.

"Although cats have a reputation for ignoring their owners, a growing body of research indicates that cats pay close attention to humans," says Kristyn Vitale, a cat behavior scientist at Unity College in Maine, who was not involved in the study. "Cats can very much learn that specific vocalizations have certain meanings," Vitale says. She notes that the study was small and that future work could expand the research to other cat populations.

Even if cats understand what we're saying, de Mouzon says, "they have a right to choose if they don't want to interact." —*Tanya Lewis*

ENGINEERING

Mighty Morpher

Turtle-inspired robot adapts its limbs to match the environment

A new transforming turtle robot can explore treacherous regions where the land meets the sea—and may lead to future machines that navigate complex real-world conditions.

Combining the best mobility features of an ocean-swimming turtle and a land-walking tortoise, the Amphibious Robotic Turtle (ART), described recently in *Nature*, can morph its limbs from turtlelike flippers to tortoiselike legs. “Most amphibious robots … use dedicated propulsion systems in each environment,” says Yale University roboticist Rebecca Kramer-Bottiglio, who is the senior author on the paper. “Our system adapts a single unified propulsion mechanism for both environments: it has four limbs, and those limbs can transition between a flipper state for aquatic locomotion and a leg state for terrestrial locomotion.”

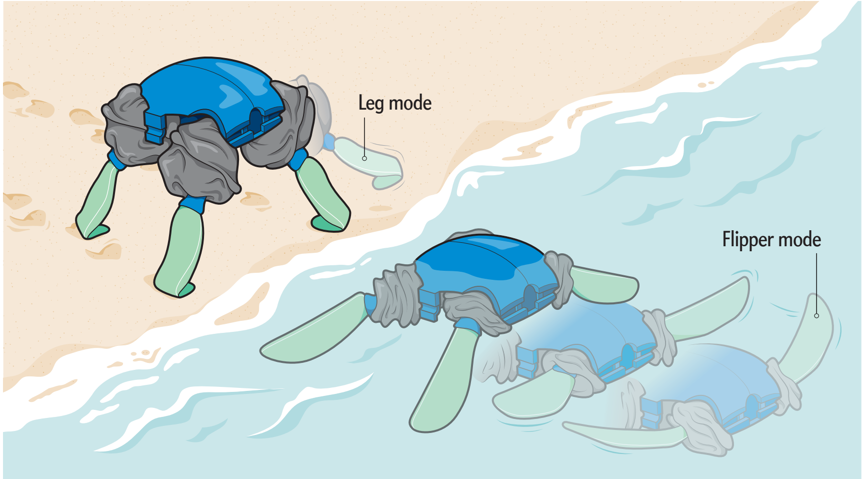
Each morphing limb is surrounded by a composite polymer material that is malleable when hot and stiff when cool. To change the limb’s shape, built-in copper heaters warm and soften the outer material. Then a soft robotic “muscle” underneath swells or deflates, shifting a flat flipper into a rounded leg, or vice versa. Finally, the polymer cools and hardens around the new shape over one to two minutes. The soft robotic limbs attach to more traditional “hard” robotic shoulder joints, which incorporate three electronic motors so ART can “crawl” or “creep” on land as well as “paddle” or “flap” in water. These joints connect to a modular chassis, where sealed PVC tubes protect the robot’s electronic components from water. A 3-D-printed “shell” gives the robot a streamlined shape and a space that can hold air or ballast to adjust buoyancy.

Integrating both soft and traditional robotics gives ART its transforming ability, says Tønnes Nygaard, a roboticist at Oslo Metropolitan University, who did not contribute to the new study. “Very strict, rigid modes of locomotion [are] a necessity when you use traditional robotic techniques,” he adds. “But now with techniques like these from soft robotics, you might be able to do something that’s a bit more fluid.”

Such adaptive techniques might eventually help robots trek across the many different surfaces and environments found in the real world, without having to tote an extra propulsion system that might make them move less efficiently. Kramer-Bottiglio’s team found that ART uses about the same amount of energy as robots built for just one environment.

The robotic tortoise isn’t at the finish line yet: the current prototype still requires a tether to provide power and communication, and its movements are slow and awkward. But the researchers are working to improve these issues. “I’m very excited to see how far they’ve come,” Nygaard says. “And I’m very interested to see what will come out of this group in a couple of years.”

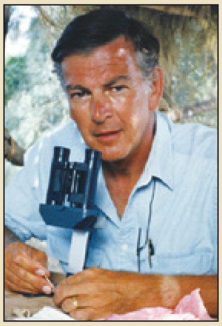
—*Sophie Bushwick*



Source: “Multi-Environment Robotic Transitions through Adaptive Morphogenesis,” by Robert Baines et al., in *Nature*, Vol. 619; October 13, 2022 (*reference*)

Graphic by Brown Bird Design

IN SCIENCE WE TRUST



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CHEMISTRY

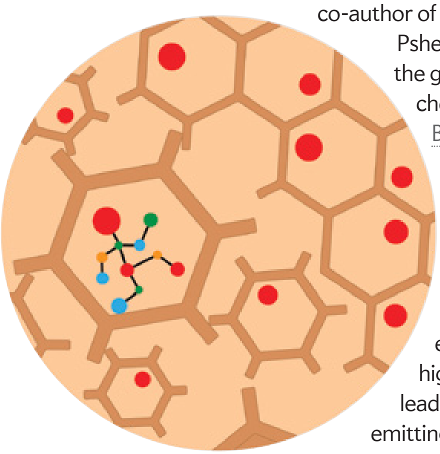
Tiny Glow

A molecule-size motor flashes and spins

One of nature's best strategies for movement at the cellular scale involves powerful molecular motors: complex molecules that transform chemical energy into mechanical energy to complete tasks such as transporting components within the cell, contracting muscle fibers and snipping apart strands of DNA.

Since 1999 chemists have been designing synthetic molecules that rotate 360 degrees in response to light or chemical stimuli. These single-function motors can generate forces on a surface, shuttle cargo to sensors and power nanoscale devices. But researchers cannot easily control or track them when they're placed within opaque biological tissue.

A newly designed molecular motor tackles both these challenges by switching between rotation and fluorescence when hit by different light wavelengths, according to a study published in *Science Advances*. "Not many compounds show two different responses to light, and this is the very first motor to show this property," says Maxim Pshenichnikov, a spectroscopist at the University of Groningen in the Netherlands and co-author of the new study.



Pshenichnikov and his colleagues, under the guidance of Groningen organic chemist and 2016 Nobel Prize winner Ben Feringa, created the double-function molecule by attaching a chemical called triphenylamine to a basic molecular motor. This let the motor respond to different light energies in different ways. Low-energy light gave the motor just enough power to rotate, whereas higher-energy light overexcited it, leading it to dispose of excess energy by emitting photons: it fluoresced. Additionally, unlike typical molecular motors driven by tissue-damaging ultraviolet light, this new compound responded to shades of infrared that can penetrate deeper under the skin without damage.

A motor like this one could aid applications that require precise pinpointing. For example, a fluorescent motor could interact with different cellular structures and light up for tracking while delivering and activating a drug. "How cool would it be if we could really follow the motor's motion in cells and use it for mechanical interference, [drug] delivery and detection?" Feringa says.

Salma Kassem, a chemist at the City University of New York, who was not involved in the study, says the design is an important step toward light-driven pharmacology: "It's challenging to combine self-reporting and functionality in one small molecule without the two properties interfering with each other. This work achieves role separation in a simple and elegant way."

The researchers intend to apply the technology to a motor with a biological function, such as binding to certain cell receptors. Then, they will test its performance in live cells or tissues. Study lead author Lukas Pfeifer, an organic chemist at the Swiss Federal Institute of Technology in Lausanne, says that this technique's success "gives me hope that we can easily transfer it to motors made with different chemical compounds." —*Rachel Berkowitz*

ANIMAL COGNITION

Bee-Ball

Playful bees raise questions about invertebrates' inner lives

Ball-rolling bumblebees have become the first insects known to "play" with inanimate objects, manipulating wood balls again and again in a series of new experiments.

When animals repeatedly engage in behavior that does not provide them with food, shelter or another immediate benefit, researchers consider the behavior play. Play with objects is widely observed in animals, although most examples come from mammals and birds.

Such behavior is one piece of the puzzle when determining whether a group of animals is sentient—whether its members have inner feelings and experiences. Scientists consider mammals, birds, and possibly even cephalopods and fish to be sentient beings. "Eventually this can tell us something more about whether [insects] are sentient," says Samadi Galpayage, a graduate student in Lars Chittka's laboratory at Queen Mary University of London and lead author of the new bumblebee study, published in *Animal Behaviour*.

For a paper published in 2017, Chittka and other scientists taught bumblebees to roll balls in exchange for a sugary prize. For their new investigation to determine whether ball rolling could be a form of play, Galpayage, Chittka and their colleagues took away the reward. First, they set up an unobstructed path for a new cohort of bees to access a feeding area's sucrose solution. Along the path's sides, the researchers placed small wood balls of

BEHAVIORAL ECOLOGY

Storm Chasers

Seabird species finds safety deep within a hurricane

Like big-wave surfers or daring meteorologists, shearwaters in the Sea of Japan deliberately head toward powerful (and dangerous) storms.

When hurricanes strike, most birds either evacuate or take shelter. After all, these storms can cause massive avian mortality. But after analyzing wind data and GPS-tracking information from 75 streaked shearwaters, British and Japanese researchers found that the seabirds sometimes navigate toward the center of hurricanes—and remain there tailing the eye for up to eight hours.

The researchers propose in the *Proceedings of the National Academy of Sciences USA* that shearwaters do this so they're not blown ashore, where they are vulnerable to crash landings and predation. The team also found that adult shearwaters handle storms better than juveniles, which lack a "map sense" of where land is.

Illustrations by Thomas Fuchs

A tracked bumblebee interacts with multicolored balls.

Richard Rickitt

varying colors, some fastened in place and some loose. Bees could access the sucrose without interacting with the balls at all.

Over 54 hours the team observed each of the experiment's 45 bees contributing to a total of 910 ball-rolling actions; younger and male bees were especially interested in rolling the balls. Feeding and ball-rolling activities happened at different times and frequencies, indicating that the bees had different motivations for the two actions. In a later experiment, scientists trained the bees to associate ball rolling with a certain chamber color. The bees then preferentially chose to enter that color chamber even when it was empty.

Although these results suggest play behavior in the bees, Galpayage says, the research does not point to any specific motivation. To determine whether the insects are gleaning pleasure from the play, for instance, investigators would need to analyze which neurotransmitters activate during ball rolling.

Olli Loukola, a behavioral ecologist at the University of Oulu in Finland, who led the 2017 ball-rolling study and was not involved in the new work, suggests the interest in moving objects could be motivated by an "innate need to develop motor skills."

Regardless of the play's function, such studies give hints about the organisms' inner lives, says Heather Browning, an animal welfare expert and philosopher at the University of Southampton in England. Evidence for many different characteristics, such as play behavior, complex brain structure and learning ability, she says, "raise the probability of sentience."

—Grace van Deelen

John Holmes/Minden Pictures

Swansea University biologist Emily Shepard, a co-author on the paper, says she's in "awe" of these master fliers—which, like their albatross relatives, use long, thin wings to soar across vast stretches of windswept ocean. (A Manx shearwater once traversed the entire Atlantic Ocean in 12 days, and sooty shearwaters in the Pacific cover up to 40,000 miles a year.)

Shepard's team found that streaked shearwaters circumnavigated storms when far out at sea. But when sandwiched between a large storm and land—and therefore at risk of being beached—several instead headed right toward the storm's eye, passing through some of its fastest winds. "Large waves and high winds are not a problem for these birds," says Josh Adams, a biologist with the U.S. Geological Survey's Western Ecological Research Center, who was not involved in the study.

Scientists had previously tracked individual albatrosses moving through cyclones, but this is the first time researchers have documented birds appearing to enter storms purposefully and strategically. Despite weighing only as much as a pint of milk, streaked shearwaters "have an inbuilt ability to cope with the strongest storms that Japan's seen," Shepard says. "It's amazing to think" that even during hurricanes, which are projected to increase in intensity because of climate change, "there will be shearwaters out there."

Other bird species, meanwhile, must flee the scene or risk drowning.

—Jesse Greenspan

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MEDICINE

Smell Detective

A super sense of smell inspires a skin-swab test for Parkinson's

A Scottish woman named Joy Milne made headlines in 2015 for an unusual talent: her ability to sniff out people with Parkinson's disease, a progressive neurodegenerative illness that is estimated to affect about 10 million people worldwide. Since then, scientists in the U.K. have been working with Milne to pinpoint the molecules that give Parkinson's its distinct olfactory signature. They have now zeroed in on a set of molecules specific to the disease—and created a simple skin-swab-based test to detect them.

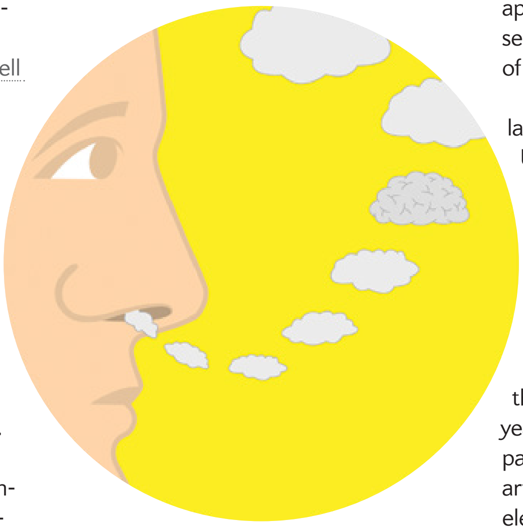
Milne, a 72-year-old retired nurse from Perth, has hereditary hyperosmia, a condition that gives her hypersensitivity to smell. She discovered that she could smell Parkinson's after noticing her husband, Les, was emitting a new, musky odor. When he was diagnosed with Parkinson's many years later, she linked this change in scent to the disease. Les died in 2015.

In 2012 Milne met University of Edinburgh neuroscientist Tilo Kunath at an event organized by the research and support charity Parkinson's UK. Though skeptical at first, Kunath and his colleagues put Milne's claims to the test. They had her smell 12 T-shirts, six from people with Parkinson's and six from nonaffected individuals. She correctly identified the disease in all six cases—and the one T-shirt from a healthy person she categorized as having Parkinson's belonged to someone who was diagnosed with the disease less than a year later.

Kunath, along with University of Manchester chemist Perdita Barran and their colleagues, subsequently used mass spectrometry to examine sebum (an oily substance found on the surface of the skin) from people diagnosed with Parkinson's. They found molecular changes suggesting alterations in the metabolism of fatty molecules known as lipids.

In Barran's latest study, published in the American Chemical Society journal *JACS Au*, she and her colleagues developed a simple skin-swab-based test to detect Parkinson's molecular signature. By comparing sebum samples from 79 people with and 71 people without the illness, the team zeroed in on a set of large lipids. These compounds could be spotted in a matter of minutes using a special type of mass spectrometry in which technicians use a piece of paper to rapidly transfer substances from a swab to an analyzer.

"I think it's a very promising set of biomarkers," says Blaine Roberts, a biochemist at Emory University, who wasn't involved in the work. He adds that one of the big open questions is how exacting this test can be. The authors of the new study reported the detailed chemical profile of the unique Parkinson's signature, but they did not include an assessment of accuracy. According to Barran, as yet unpublished data suggest that their test may be more than 90 percent accurate in determining whether a person has Parkinson's.



Tiago Outeiro, a neuroscientist at the University of Göttingen in Germany, who was not involved with the research, says the sebum-based swab test is novel. He adds that one clear advantage it has over other methods—such as blood tests—that probe for Parkinson's biomarkers is the ease of sample collection. Outeiro wonders whether people with diseases that share symptoms and pathologies with Parkinson's, including multiple system atrophy, also have similar chemical markers.

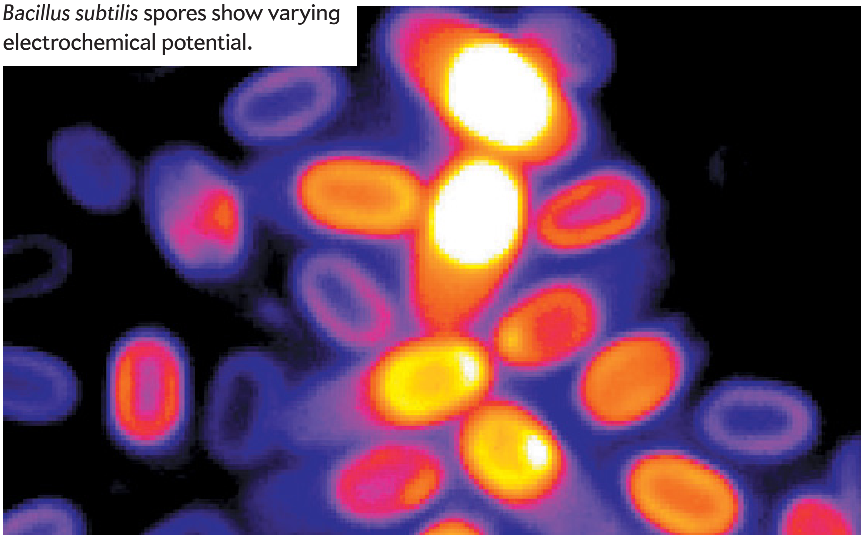
The researchers are now working with local hospitals to ascertain whether their sebum-based test can also be conducted in clinical laboratories—a key step toward determining whether it would work as a diagnostic tool. Ultimately, Barran says, the researchers hope to use the test to help secure a faster diagnosis for individuals with suspected Parkinson's who have been referred to neurologists by a general practitioner. Thousands of such people are currently waiting to see neurologists in the U.K.'s National Health Service, for instance, and it will take an estimated two years to clear that list, Barran says. The new tool could let those patients mail in skin swabs to be analyzed in a hospital lab, pinpointing those who need help most urgently. Barran's research team is approaching people on the waiting list to see if they are willing to take part in a trial of this triage process.

Barran and her colleagues are also collaborating with researchers at Harvard University to determine whether sebum-based biomarkers are detectable in people who have unexplained constipation, a reduced sense of smell or other possible early signs of Parkinson's but have not yet received a diagnosis.

Milne has also inspired other scientists to search for biomarkers based on the disease's olfactory signature. Last year investigators in China published a paper describing an electronic nose—an artificial-intelligence-based sensor modeled after the olfactory system—that sniffs out a set of nonlipid molecules present in the sebum of patients with Parkinson's. Other groups in China, the U.K. and elsewhere have been training dogs to sniff out the disease.

And Parkinson's may not be the only disease Milne has a nose for. She has also reported noticing unique smells in people with Alzheimer's, cancer and tuberculosis, and she is working with scientists to see whether specific olfactory signatures of those diseases can be identified.

Milne says she hopes this research will ultimately benefit patients with these conditions. "My husband suffered from [Parkinson's] for 21 years after his diagnosis, but he had it many years before that," Milne told Scientific American in 2015. "I would like to see that people don't suffer the way he suffered." —*Diana Kwon*



Bacillus subtilis spores show varying electrochemical potential.

Kaito Kikuchi and Leticia Galera/SüelLab

MICROBIOLOGY

Electric Countdown

Do spores dream of electric sheep?

Sometimes procrastination pays off. When their environment gets too stressful, many bacteria stuff some of their innards into ultratough packets called spores, which shut down and wait—potentially for centuries—for things to improve. How do these seemingly dead specks sense optimal conditions for revival? A new study in *Science* reveals that bacterial spores can decide when to wake up by setting an electric alarm.

Starvation, radiation, scorching heat, freezing cold, even the vacuum of space—none is particularly concerning to a spore. But they seem "useless" otherwise, says study author and biophysicist Gürol Süel of the University of California, San Diego. "If you took these cells to the hospital," he says, "they'd be pronounced dead on arrival."

Spores are only indestructible while they're dormant. So they have to avoid waking up (or "germinating") when conditions are unfavorable, says biochemist Peter Setlow of the University of Connecticut, who was not involved in the study: "If you make the wrong decision and you come back to life, you are dead."

This study reveals one way spores make that decision. To form a spore, a bacterium creates a copy of its DNA, packs it into a little compartment, wraps the entire thing in a protective coat and then bursts open, releasing the spore (and dying in the process). The forming spore stockpiles charged potassium ions, creating a "biological capacitor" that stores electrical energy, Süel says. Whenever the spore encounters nutrients, a bit of its potassium trove leaks out, dissipating some of the charge. Once this happens enough times, the stored energy dips below a threshold, and the spore germinates—with reasonable chances of not starving.

"This is a significant advance in the field," Setlow says. "It brings up a whole new way of thinking about germination." Knowing how spores "count" nutrients could improve food safety, because spore-forming bacteria can survive harsh sterilization procedures and revive to cause food poisoning. Dormancy also helps some disease-causing germs evade attack; waking them early could improve treatments, so "there's a lot of applied interest in how to get spores to germinate rapidly," Setlow adds.

The study results hint that ionic countdowns may be fundamental to life on Earth, Süel says. Neurons also count with electricity to know when to fire; the researchers found that formulas that describe neurons neatly predict spore behavior, too. Venus flytraps snap shut using an electric countdown, and all cells harness ion flows to process energy.

"These electrical potentials are not a recent invention. They're billions of years old," Süel says. "What other aspects of biology can we better understand by keeping in mind that it's not just all about gene expression and proteins and DNA—but these charged ions?" —*Elise Cutts*

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BIOMIMICRY

Science in Images

By Maddie Bender

The concentric circles or eyespots on butterfly and moth wings—like those seen on this Suraka silk moth—not only look like real eyes but may also appear to glare directly at predators from many directions, scientists have found. This optical illusion, called the "Mona Lisa effect," could scare would-be attackers and buy the insects enough time to escape.

Scientists suspect that eyespots, with dark "pupils" in the center surrounded by lighter "irises," look like real eyes to predators. Hannah Rowland, an ecologist at the Max Planck Institute for Chemical Ecology in Jena, Germany, wanted to see if the direction of this fake gaze contributed to the effect. Her study results were published recently in *Frontiers in Ecology and Evolution*.

First, Rowland and her co-author trained chicks to attack a mealworm hidden behind a paper printout of two eyespots at the end of a runway. When the eyespots' pupils were specifically pointed in the chicks' direction, the birds repeatedly ran toward the paper and then backed away, and they waited a few minutes before attacking—signs of wariness. But when the pupils instead appeared to look away from the direction of the chicks' approach, the birds attacked in seconds. Centrally located pupils, though not as effective as ones that peered directly toward the chicks, resulted in longer delays than pupils that looked the other way.

"This suggests that they really are paying attention to the direction of the pupils in the eyespots and are perceiving them as eyelike stimuli," Rowland says. The concentric eyespots found most often in the insect world, she adds, may seem to the chicks like a pair of eyes that follow them, irrespective of approach angle.

National University of Singapore evolutionary biologist Antonia Monteiro, who was not involved in the research, says the study is a "cool" demonstration of an evolutionary theory for eyespots.

"These butterflies can be encountered from all angles, so having the pupil centrally located ends up being pretty good," Monteiro says. Still, she says, the eyespots used in the study were several millimeters larger than even the largest commonly found in nature, raising the possibility that the chicks may have been extra frightened by the size of the paper eyes.

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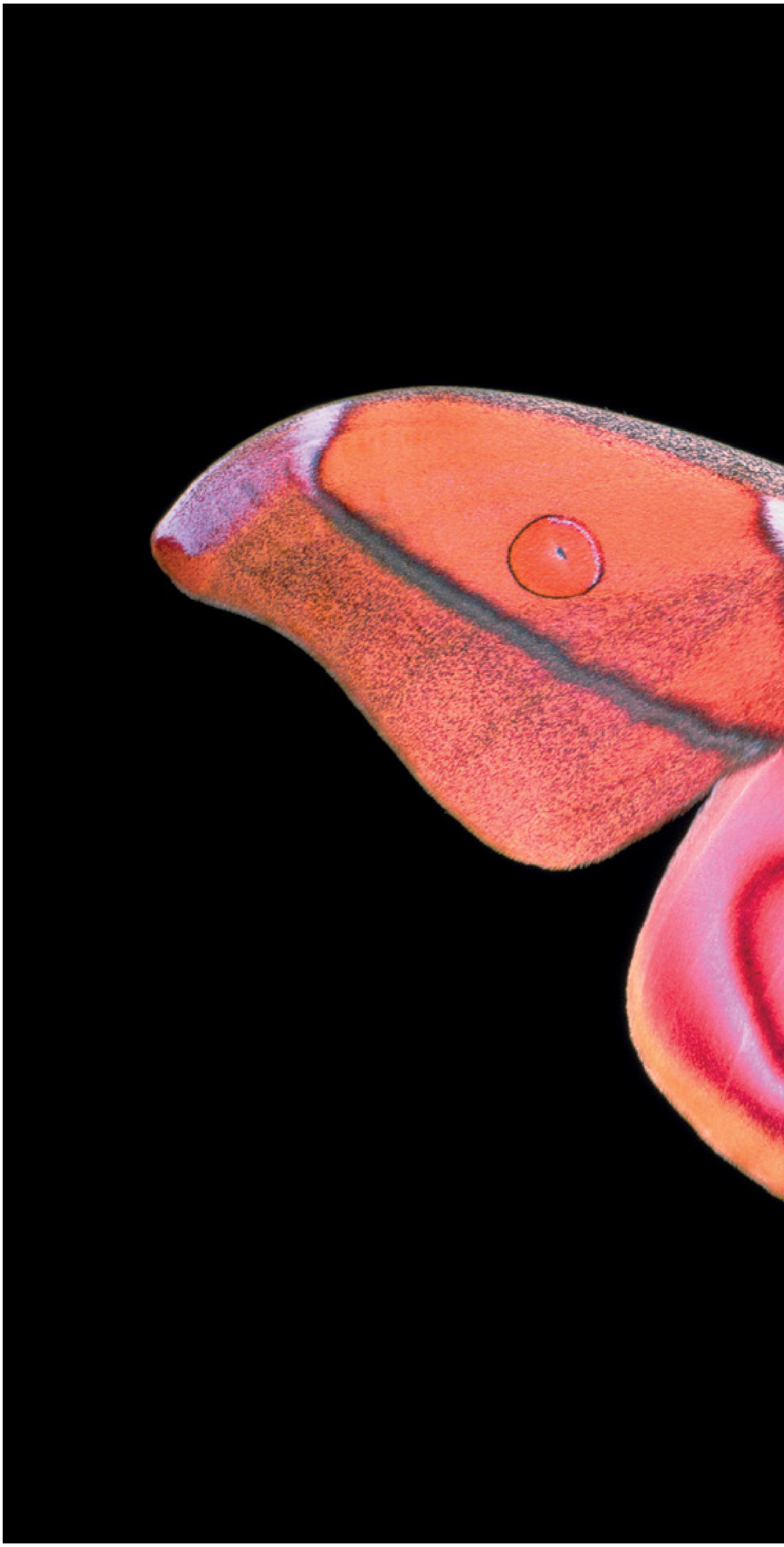


Mitsuhiko Imamori/Minden Pictures

NEWS AROUND THE WORLD

Quick Hits

By Daniel Leonard

CANADA

Narwhals seem to be migrating later every year as ice-coverage patterns change in Arctic waters. The unicornlike whales were thought to be particularly vulnerable to climate change because of their 100-year life spans and slow evolution, so this behavioral shift bodes well for their adaptability.

MALDIVES

Researchers have identified a new type of ecosystem, which they have named the "trapping zone," in the Indian Ocean. In it, swarms of tiny traveling animals get stuck among rocks and reefs, becoming easy prey for sharks and other large predators.

PAPUA NEW GUINEA

Scientists found evidence that a giant kangaroo species that walked on all fours lived in New Guinea until 20,000 years ago, thousands of years after most megafauna went extinct in neighboring Australia. The researchers suspect giant mammals lasted longer on the island because far fewer humans lived there.

SAUDI ARABIA

Drone footage suggests the Saudi government has begun constructing a city that officials have claimed will be 105 miles long and 0.1 mile wide—and enclosed within giant mirrors to blend with the landscape. The city is designed to be traversable by foot or rail, with a low carbon footprint.

SPAIN

Neandertal teeth recovered from Gabasa indicate these ancient human relatives were primarily carnivores. The teeth have low zinc 66, consistent with a meaty diet—which challenges prior work suggesting Neandertals were more omnivorous.

ZAMBIA

A study of chimpanzees at the Chimfunshi Wildlife Orphanage Trust shows the animals instinctively synchronize their steps when walking next to each other. This behavior is also seen in humans, suggesting that the unthinking coordination of basic motions is a shared ancestral trait.

For more details, visit www.ScientificAmerican.com/jan2023/advances

HEALTH

The Walking Dental

Bacteria and fungi glom together to crawl across our teeth, spreading decay

Most of us would rather not think about the cavity-causing microbes infesting our mouths. They coat our teeth, eat the same sugars we do and excrete acids that carve holes in our enamel. And the complete picture is even grosser.

A new study published in the *Proceedings of the National Academy of Sciences USA* shows that conglomerations of fungi and bacteria can work together to "walk" and "leap" across the surface of teeth, spreading decay much faster than either organism alone.

"The knowledge in the past was that it was just bacteria accumulating one by one and causing cavities," says study co-author Hyun (Michel) Koo, a microbiologist and dentist at the University of Pennsylvania. His team collected saliva samples from toddlers with severe tooth decay and found natural assemblages of *Streptococcus mutans* bacteria and *Candida albicans* fungi, which weren't present in saliva from children with healthier teeth. Viewing these masses under a microscope revealed a surprise: they appeared to be capable of complex motion.

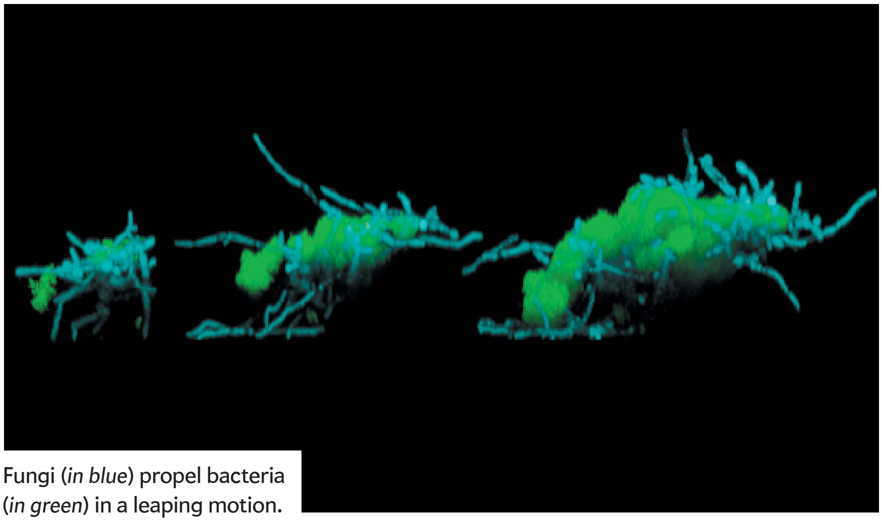
Small bacterial cells tended to cluster around the core of each clump, forming a sticky binding that held everything together. Larger, rod-shaped fungal cells joined on the outside as moving "limbs" that propelled the structure forward as it grew. The front limbs sometimes appeared to walk or even jump ahead, with the assemblage rapidly expanding in one direction as its hind limbs remained on the ground. If two such groupings were near each other, they would sometimes reach out in a "handshake" and then merge.

Microbes in the mouth "are like a community trying to expand their territory," gaining new land and sugary resources, says Zhi Ren, a postdoctoral fellow in Koo's laboratory and co-lead author on the study. The team found that bacterial-fungal partnerships grew faster and were more resistant to removal by mechanical force or antimicrobial chemicals than fungi or bacteria alone.

"What this paper really adds is the spatial-temporal aspect of these structures' behavior," says Judith Behnsen, a microbiologist at the University of Illinois at Chicago, who was not involved in the new research. She says most microscopy researchers examine microbes suspended in place by a preservative chemical, but this study followed living, moving organisms: "When I saw the images in the paper, I was blown away."

Future research could determine who is most at risk of developing bacterial-fungal assemblages and the best way to treat them, Ren says. Tooth decay is extremely common and dangerous globally, he adds—and studying the interactions between bacteria and fungi can help us defend against their territorial expansion.

—Daniel Leonard



Fungi (*in blue*) propel bacteria (*in green*) in a leaping motion.

Zhi Ren

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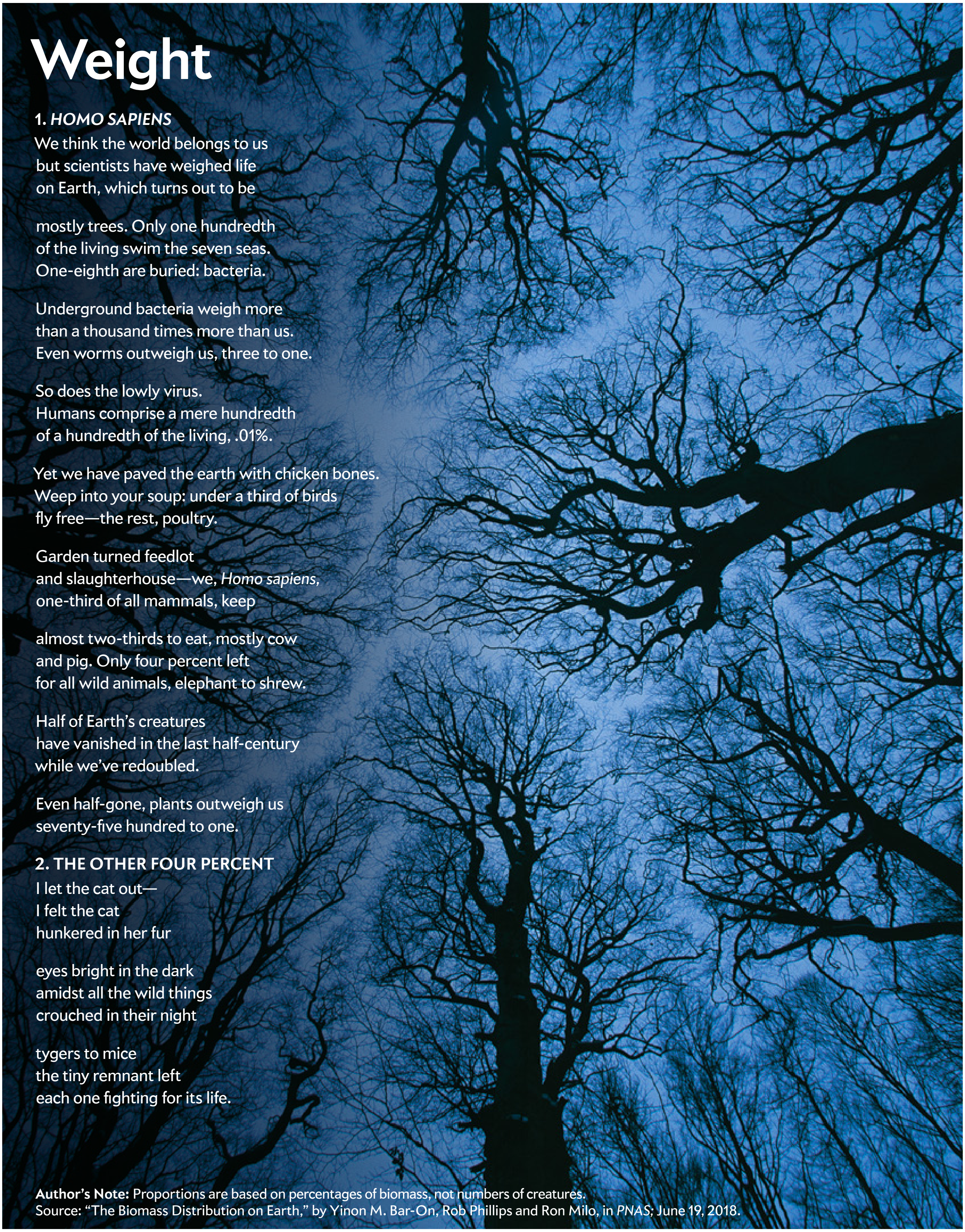
METER

Edited by Dava Sobel

Barbara Ungar's forthcoming collection of poems is *After Naming the Animals*. Her other published collections include *Save Our Ship; Immortal Medusa; Charlotte Brontë, You Ruined My Life;* and *The Origin of the Milky Way*. She is a professor of English at the College of St. Rose in Albany, N.Y.



Weight

1. *HOMO SAPIENS*

We think the world belongs to us
but scientists have weighed life
on Earth, which turns out to be

mostly trees. Only one hundredth
of the living swim the seven seas.
One-eighth are buried: bacteria.

Underground bacteria weigh more
than a thousand times more than us.
Even worms outweigh us, three to one.

So does the lowly virus.
Humans comprise a mere hundredth
of a hundredth of the living, .01%.

Yet we have paved the earth with chicken bones.
Weep into your soup: under a third of birds
fly free—the rest, poultry.

Garden turned feedlot
and slaughterhouse—we, *Homo sapiens*,
one-third of all mammals, keep

almost two-thirds to eat, mostly cow
and pig. Only four percent left
for all wild animals, elephant to shrew.

Half of Earth's creatures
have vanished in the last half-century
while we've redoubled.

Even half-gone, plants outweigh us
seventy-five hundred to one.

2. THE OTHER FOUR PERCENT

I let the cat out—
I felt the cat
hunkered in her fur

eyes bright in the dark
amidst all the wild things
crouched in their night

tygers to mice
the tiny remnant left
each one fighting for its life.

Author's Note: Proportions are based on percentages of biomass, not numbers of creatures.
Source: "The Biomass Distribution on Earth," by Yinon M. Bar-On, Rob Phillips and Ron Milo, in *PNAS;* June 19, 2018.

Christian Ziegler/Minden Pictures

Claudia Wallis is an award-winning science journalist whose work has appeared in the *New York Times, Time, Fortune* and the *New Republic.* She was science editor at *Time* and managing editor of *Scientific American Mind.*

A Diet for Better Bones

Surprising findings on the roles of vitamin D, coffee and alcohol

By Claudia Wallis

Among my friends, many of whom are women of a certain age, one topic seems to dominate our conversations about health: bones. It makes sense, given that 20 percent of American women ages 50 and older have osteoporosis and that more than half have detectable bone loss (osteopenia). For men, the respective figures are lower: 4 percent and a third. Worldwide, one out of three women over age 50 and one out of five older men will develop an osteoporotic fracture—a hip, a wrist, a vertebra or two. Another reason for the endless jawboning about bones is mass confusion over how best to strengthen your skeleton and whether diet and supplements really make a difference.

Diet research is always messy, and study results on nutrition and bone health have been wildly inconsistent. But gradually some clarity is emerging. As we draw up resolutions for what to eat in the coming year, it's useful to look at new data on vitamin D, as well as recent research on coffee and other foods.

Bone is a dynamic tissue, constantly replenished with new cells. Calcium is the key nutrient for building bone, and vitamin D enables the gut to absorb calcium from the food we eat, so doctors often recommend D supplements to counteract age-related bone loss. Today more than a third of American adults ages 60 and older pop this vitamin.

But to the surprise of many, a huge study published this past summer in the *New England Journal of Medicine* found that taking vitamin D for five years did not reduce the rate of fractures in healthy adults ages 50 and older. That result built on earlier findings, led by the same team, that D supplements do not improve bone density (or, for that matter, lower the risk of cancer or heart disease). An editorial accompanying the fracture study declared that it's time for medical professionals to stop pushing these pills and quit ordering so many blood tests for vitamin D levels.

"Food and incidental sun exposure likely provide enough vitamin D for healthy adults," says endocrinologist Meryl LeBoff of Brigham and Women's Hospital in Boston, who led the study. But LeBoff puts an emphasis on "healthy" adults. The study did not focus on those who already have osteoporosis and/or take medications for it. Such people would be wise to remain on extra vitamin D and calcium, she advises.

What does help maintain strong bones for all of us? The easy answer is foods that are high in calcium, such as dairy products, sardines and tofu. Health authorities recommend a lot more calcium than most of us routinely get: 1,300 daily milligrams for kids ages nine through 18 who are building bone density for a lifetime, 1,000 daily mg from age 19 to 50 and 1,200 mg for women after 50 and men after 70. Federal surveys indicate that only 61 percent of Americans and just half of children hit these targets, which, admittedly, takes some effort. For example, you would need to eat at least three daily cups of plain yogurt or nearly nine cups of cottage cheese to get 1,200 mg of calcium. Getting it from food is best, LeBoff says, "because there are so many other nutrients, and you have a more continuous absorption than with a pill."

For those of us who like to start our day with coffee, modest consumption may help our bones. Although very high levels of caffeine—say, six to eight cups of coffee—cause calcium to be lost in urine, one or two cups seems to have a beneficial effect. A study led by Ching-Lung Cheung of Hong Kong University linked three digestive by-products of coffee with greater bone density at the lumbar spine or upper thigh bone. "Coffee intake, if not excessive, should be safe for bone," he says, "and if you still have concerns, add milk!"

Alcohol, too, is best in moderation. Excessive drinking can disrupt the body's production of vitamin D and interfere with hormones that promote bone health. On the other hand, fizzy water has been wrongly maligned: it does not weaken bones, although evidence suggests that cola and soda pop may do so.

The other key element of skeletal health involves calories out rather than calories in. Weight-bearing exercise stimulates bone formation throughout life. And you don't have to heft dumbbells. Just supporting your own weight while walking, running or jumping does the trick. So while boning up on better nutritional choices, add more exercise to your menu of New Year's resolutions. SA

Illustration by Jay Bendt

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EVOLUTION

THE HUMAN ENGINE

Studies of metabolism reveal surprising insights into how we burn calories—and how cooperative food production helped *Homo sapiens* flourish

By Herman Pontzer

Illustration by Eva Vázquez

Herman Pontzer is a professor of evolutionary anthropology at Duke University. He studies how evolution has shaped human physiology and health. He is author of *Burn: New Research Blows the Lid Off How We Really Burn Calories, Stay Healthy, and Lose Weight* (Avery, 2021).

IT WAS MY DAUGHTER CLARA'S SEVENTH BIRTHDAY PARTY, A SCENE AT ONCE FAMILIAR AND bizarre. The celebration was an American take on a classic script: a shared meal of pizza and picnic food, a few close COVID-compliant friends and family, a beaming kid blowing out candles on a heavily iced cake. With roughly 380,000 boys and girls around the world turning seven each day, it was a ritual no doubt repeated by many, the world's most prolific primate singing "Happy Birthday" in an unbroken global chorus.

Such a wholesome setting seems an unlikely place for rampant rule breaking. But as an evolutionary anthropologist, I can't help but notice the blatant disregard our species shows for the natural order. Nearly every aspect of our modern lives marks a cheerfully outrageous departure from the laws that govern every other species on the planet, and this birthday party was no exception. Aside from the fresh veggies left wilting in the sun, none of the food was recognizable as a product of nature. The cake was a heat-treated amalgam of pulverized grass seed, chicken eggs, cow milk and extracted beet sugar. The raw materials for the snacks and drinks would take a forensic chemist years to reconstruct. It was a calorie bonanza that animals foraging in the wild could only dream about, and we were giving it away to people who didn't even share our genes. All this to celebrate some obscure astronomical alignment, the moment our planet swept through the same position relative to its star as on the day my daughter was born. At seven years old, most mammals are grandparents if they're lucky enough to be alive. Clara was still a kid, dependent on us for food and shelter and years away from independence.

Humans weren't always such scofflaws. We come from a good Family. The living apes, our closest relatives, are well-behaved primates, eating fruit and leaves straight from the tree and nibbling on the occasional meal of insects or small game. Like every other mammal, apes learn early to fend for themselves, foraging on their own as soon as they're weaned, and they know better than to give their hard-earned food away. Fossils from deep in the human lineage, the first four million years after we broke from the other apes, indicate our early ancestors played by the same ecological rules.

Around 2.5 million years ago things took an unlikely turn. Early populations of the genus *Homo* stumbled onto a new way of making a living, something unprecedented in the history of life. Instead of pursuing a career as a plant eater, carnivore or generalist, they tried a strange, dual strategy: some would hunt, others would gather, and they'd share whatever they acquired. This cooperative approach placed a premium on intelligence, and over millennia brain size began to increase. Our Paleolithic ancestors learned to knap delicate blades from round stone cobbles, hunt large game and cook their food. They built hearths and homes and began changing the landscape, developing an ecological mastery that led eventually to farming.

These evolutionary shifts reverberate today. The cooperative foraging that pushed our hunting, gathering and farming ancestors to flout long-established ecological rules didn't just change the foods we eat. It altered fundamental aspects of our biology, including our metabolism. The same unlikely series of events that gave us birthday cake has also shaped the way we eat it—and how we use the calories.

For all the talk about metabolism in the exercise and dieting worlds, you would think the science was settled. In reality, we've been embarrassingly short on hard data about the calories we burn each day and how we evolved to obtain them. But recently my colleagues and I have made important strides in understanding how our bodies use energy. Our findings have overturned much of the received wisdom about the ways human energy requirements change over the course of a lifetime. And, as we've discovered in a parallel effort, our energy needs are deeply intertwined with the evolution of our food-production strategies: foraging and farming. Together these studies provide the clearest picture yet of the inner workings of the human engine—and how our strategy for earning, burning and sharing calories underpins our extraordinary success as a species.

ENERGY BUDGETS

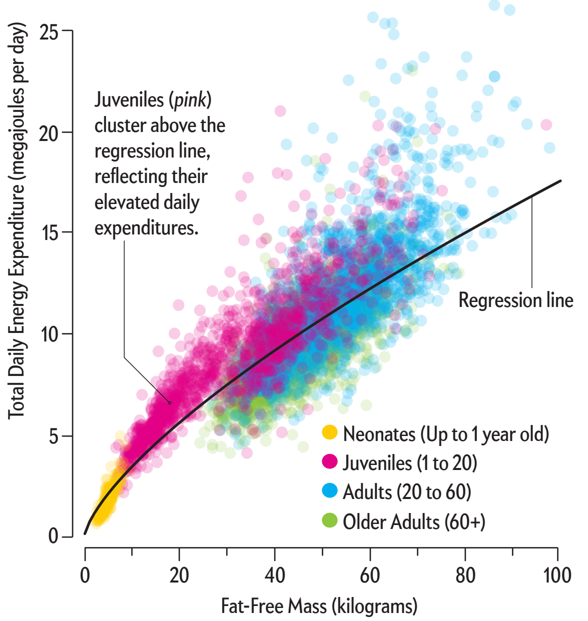
OUR BODIES are wonders of coordinated chaos. Every second of every day, each of your 37 trillion cells is hard at work, pulling in nutrients, building new proteins and doing the myriad other tasks that keep you alive. All of this work takes energy. Our metabolism is the energy we expend (or the calories we burn) each day. That energy comes from the food we eat, and so our metabolism also sets our energy requirements. Calories in, calories out.

Evolutionary biologists often think about metabolism as an organism's energy budget. Life's essential tasks, including growth, reproduction and bodily maintenance, require energy. And every organism must balance its books.

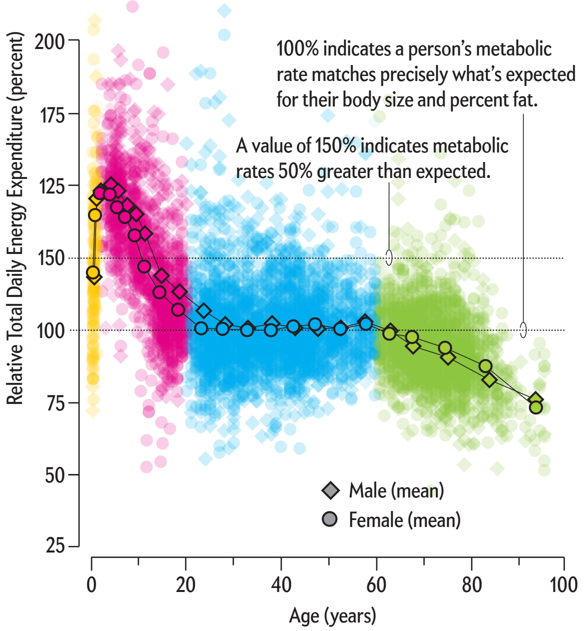
Measuring Metabolism

The first comprehensive study investigating the effects of age and body size on daily energy expenditure has upended much of the conventional wisdom about metabolism. Metabolic rates increase with body size, as expected. But they are not inherently different in men and women, nor do they decline with middle age, among other revelations from this research.

The greatest predictor of metabolism is fat-free mass. Larger bodies generally burn more calories.



Metabolism skyrockets over the first year of life. Daily energy expenditures hold remarkably steady from age 20 to 60.



Source: "Daily Energy Expenditure through the Human Life Course," by Herman Pontzer et al., in *Science*, Vol. 373; August 2021 (*reference*); restyled by Jen Christiansen

Humans are a striking example of this evolutionary bookkeeping in action. The traits that distinguish us from the other apes, including our huge brains, big babies and long lives, all require a lot of energy. We pay for some of these costs by spending less on our digestive system, having evolved a shorter intestinal tract and smaller liver. But we have also increased our metabolic rate and the size of our energy budget. For our body size, humans consume and burn more calories each day than any of the other apes. Our cells have evolved to work harder.

The work our bodies do changes as we age, the activities of our cells waxing and waning in a choreographed dance from growth to adulthood to senescence. Tracking those changes through our metabolism could provide a better understanding of the work our cells do at each age as well as our changing calorie needs. But a clear audit of our metabolism over the human life span has been hard to obtain.

It's obvious that adults need more calories than infants—bigger people have more cells doing more work, so they burn more energy. We also know that elderly people tend to eat less, although that's often accompanied by a loss of body weight, particularly muscle mass. But if we want to know how active our cells are and whether metabolism gets faster or slower as we grow up and grow old, we need to separate the effects of age and size, which is not easy. You need a large sample with people of all ages, measured with the same methods. Ideally, you'd want measures of total daily energy expenditure, a full tally of the calories used each day.

Researchers have been measuring metabolic rates at rest for more than a century, with some evidence for faster metabolism in children and slower metabolism among the elderly. Yet resting metabolism accounts for only 60 percent or so of the calories we burn over 24 hours and doesn't include the energy we spend on exercise and other physical activity. Online calorie calculators purport to include activity costs, but they're really just a guess based on your self-reported weight and physical activity. In the absence of solid evidence, a kind of folk wisdom has developed, cheered on and cultivated by charismatic hucksters selling metabolic boosters and other snake oil. We're often told our metabolism speeds up at puberty and slows down in middle age, particularly with menopause, and that men have faster metabolisms than women. None of these claims is based on real science.

A METABOLIC DATABASE

MY COLLEAGUES and I have begun to fill that gap in scientific understanding. In 2014 John Speakman, a researcher in metabolism with laboratories at the University of Aberdeen in Scotland and the Chinese Academy of Sciences in Shenzhen, organized an international effort to develop a large metabolic database. Crucially, this database would focus on total daily energy expenditure measured using the doubly labeled water method, an isotope-tracking technique that measures the carbon dioxide produced by the body (and thus the calories burned) over one to two weeks. Doubly labeled water is the gold standard for measuring daily energy expenditures, but it's expensive, and you need a specialized lab for the isotope analyses. So even though this technique has been around for decades, studies are typically small. Led by Speakman, my lab joined a dozen others around the world in pooling decades of data. We ended up with more than 6,400 measurements of people ranging from babies just eight days old to men and women in their 90s.

In 2021, after years of collaborative effort, we published the first comprehensive study investigating the effects of age and body size on daily energy expenditure. As expected, we found that metabolic rates increase with body size: bigger people burn more calories. In particular, fat-free mass (the muscles and other organs) is the single strongest predictor of daily energy expenditure. This makes good sense. Fat cells aren't as active as those in the liver, brain, or other tissues, and they don't contribute much to your daily expenditure. More important, with the relation between mass and metabolic rate clearly established from thousands of measurements, we could finally test whether metabolism at each age was faster or slower than we'd expect from size.

The results were a revelation, the first clear road map of metabolism over the human life span.

The results were a revelation, the first clear road map of metabolism over the human life span. We found that, metabolically, babies are born like tiny adults, reflecting their development as part of their mom's energy budget. But metabolism skyrockets over the first year of life, so that by their first birthday children are burning 50 percent more energy than we'd expect for their size. Their cells are far busier than adults' cells, hard at work on growth and development. Earlier studies measuring glucose uptake in the brain during childhood suggest some of this work is neuronal growth and synapse development. Maturation in other systems no doubt contributes as well. Metabolism stays elevated through childhood, slowly decelerating through adolescence to land at adult levels around age 20. Boys decline more slowly than girls, consistent with boys' slower development, but there's no bump at puberty in males or females.

Perhaps the biggest surprise was the stability of our metabolism through middle age. Daily energy expenditures hold remarkably steady from age 20 to 60. No middle age slowdown, no change with menopause. The weight gain so many of us experience in adulthood cannot be blamed on a declining metabolism. As a man in my 40s, I had sort of believed the folk wisdom that metabolism slowed as we aged. My body definitely feels different than it did 10 or 20 years ago. But like hunting some metabolic Sasquatch, when you actually look there's nothing there. Same for the much touted metabolic differences between men and women. Women have lower daily energy expenditures on average, but that is only because women tend to be smaller and carry more of their weight as fat. Compare men and women with the same body weight and body fat percentage, and the metabolic difference disappears.

We did find a decline in metabolism with age, but it doesn't kick in until we hit 60. After 60, metabolism slows by around 7 percent per decade. By the time men and women are in their 90s, their daily expenditures are 20 to 25 percent lower, on average, than those of adults in their 50s. That's after we account for body size and composition. Weight loss with old age, especially diminished muscle mass, compounds the decline in expenditure. As with all age groups, there's a good amount of individual variability. Maintaining a younger, faster metabolism into old age might be a sign of aging well, or perhaps it is even protective against heart disease, dementia and other age-related disease. We can now start to investigate these connections. Guided by our metabolic road map, we have a new world of research ahead of us.

What is already apparent, however, is that a bite of birthday cake does different things for a seven-year-old girl, her middle-aged dad and her elderly grandmother. Clara's bite is likely to be gobbled up by busy cells, fueling development. Mine might go to maintenance, repairing all the little bits of damage accrued through the course of the day. As for Grandma, her aging cells might be slow to use the calories at all, storing them instead as glycogen or fat. Indeed, for any of us, the cake will end up as fat if we eat more calories than we burn.

The road map also highlights a major conundrum of the human condition. Whether they're born into a hunter-gatherer camp, a farming village or an industrial megacity, human youngsters need a lot of help getting food. Other apes learn to forage for themselves by the time they stop nursing, around the age of three or four. Our children are wholly dependent on others for food for years and aren't self-sufficient until their teens. And those least able to fend for themselves have the greatest energy needs. Not only has our species evolved a faster metabolic rate and greater energy demands than other apes, but we must also provision each costly offspring for more than a decade. Where do we get all those calories? Recently my colleagues and I worked out this part of the human energy equation, too.

COSTLY KIDS

THE QUESTION OF CALORIES looms largest in hunter-gatherer and farming communities, where daily life revolves around food production. For most of our species' history, as for most species, there was no other line of work. Every kid knew what they were going to be when they grew up. As late as the mid-1800s, more than half of the American workforce was made up of farmers.

For the past decade I've been working with colleagues to understand the calorie economy in the Hadza community of northern Tanzania. The Hadza are a small population of 1,000 or so, and about half of them maintain a traditional hunting-and-gathering way of life, foraging on the savanna landscape they call home. No population alive today is a perfect model of the past, but groups like the Hadza, who continue these traditions, provide a living example of how these systems work. Men spend most days hunting with bow and arrow or chopping into hollow tree limbs to pillage honey from beehives. Women gather berries and other plant foods or dig for wild tubers in the rocky soil. Hadza camps, small collections of grass houses tucked among the acacia trees, are alive all day with kids being kids, running around, laughing, playing—and waiting for adults to bring them food.

We've measured Hadza energy budgets using doubly labeled water, giving us a clear idea of the calories men and women consume and expend each day. We've also lugged portable respirometry equipment into the bush, a metabolic lab in a briefcase, to measure the energy costs of foraging activities such as walking, climbing, digging tubers and chopping trees. And we've got years of careful observation recording the hours spent each day on different foraging tasks and the amount of food acquired. After more than a decade of work, we've got a complete accounting of the Hadza energy economy: the calories spent to get food, the calories acquired, the proportions shared and consumed.

Tom Kraft of the University of Utah led our team's effort to compare the energy budgets of the Hadza population with similar data from other human groups and from other species of apes. It was a massive project, poring over old ethnographic accounts of hunter-gatherer and farming groups and combing through ecological studies and doubly labeled water measurements in apes to reconstruct their foraging economies. But when we were finished, what emerged was a new understanding of the energetic foundation for our species' success. We could finally see where all those calories come from, the energy needed to fuel expensive human metabolisms and provision helpless kids.

CLEVER COOPERATORS

IT TURNS OUT humans' unique, cooperative foraging strategy, combined with our clever brains and tools, makes hunting and gathering extremely productive. Even in the harsh, dry savanna of northern Tanzania, Hadza men and women acquire 500 to 1,000 kilocalories of food an hour, on average. Ethnographic records from other groups around the world suggest these rates are typical for hunter-gatherers. Five hours of hunting and gathering can reliably bring in 3,000 to 5,000 kilocalories of food, enough to meet a forager's daily needs and provision the camps' children.

It's the positive feedback engine that propelled the human species to new heights. Hunting and gathering is so productive that it creates an energy surplus. Those extra calories are channeled to offspring, meaning they can take longer to develop, learning skills that make them effective foragers. Reaching adulthood, they'll do just as their parents did, acquiring extra food and plowing those calories into the next generation. Over evolutionary time childhood grows longer as foraging strategies grow more complex. Life spans get extended, too, with natural selection favoring additional years of productive foraging to support children and grandchildren. Grandparents, once rare, become a fixture of the social network.

Apes in the wild are not nearly as productive in gathering food. A forensic accounting of the energy budgets for chimpanzees, gorillas and orangutans shows that males and females get around 200 to 300 kilocalories an hour. It takes them seven hours of foraging just to meet their own needs each day. No wonder they don't share.

Our hyperproductive foraging isn't cheap. People in hunter-gatherer communities expend more than twice as much energy to acquire food as apes in the wild. Surprisingly, human technology and smarts don't make us very energy-efficient. Hadza men and women achieve the same paltry ratio of energy acquired to energy expended that we find in wild apes. Cooperation and culture enable human foragers to be incredibly time-efficient, acquiring lots of calories an hour, but our unique foraging strategies are still energetically demanding. Hunting and gathering is hard work.

Farming isn't any easier, but our analyses found it can be even more productive. When we compared the energy budgets for the Hadza and other hunter-gatherer populations with those of traditional farming groups, we found that farmers typically produce far more calories an hour. The Tsimane community, a population in the Amazonian rain forest of Bolivia, provides a useful point of comparison. The Tsimane get most of their calories from farming, but they also hunt, fish and collect wild plants. With farmed foods as their energy staple, they produce nearly twice as many calories an hour as the Hadza. They're more energy-efficient as well, getting more food from every calorie they spend foraging and farming.

Those extra calories are embodied in the children running around Tsimane villages. More food and faster production mean a lighter workload for mothers because others in the community can more easily share the time and energy costs of caring for kids. As with many subsistence farming communities, Tsimane families tend to be large. Women have an average of nine children over the course of their lives. Compare that with the average fertility rate of six children per mother in the Hadza community, and the impact of that extra energy is inescapable. And it's not just the Tsimane. Farming communities tend to have higher fertility rates than hunter-gatherer communities. Increased fertility is an important reason farming overtook hunting and gathering in the Neolithic age, the time spanning roughly 12,000 to 6,500 years ago. Archaeological sites across Eurasia and the Americas document a rising tide of children and adolescents following the development of agriculture.

HAVING OUR CAKE

FROM THIS PERSPECTIVE, a kid's birthday party is more than a personal milestone. It's a celebration of our improbable evolutionary story. There's the food, of course. We get the flour and sugar for the cake from our farming ancestors, the fire to bake it from the Paleolithic era. The milk and eggs come from animals that we've completely transformed from species we once hunted, shaped to our will over generations of careful husbandry. And there's the calendar we use to mark our days and measure our years, an invention of agriculturalists who needed to know precisely when to reap and sow. Hunter-gatherers track the seasons and lunar cycles but have little use for accurate annual calendars. There are no birthdays in a Hadza camp.

But the key element of any celebration is the community of friends and relatives, multiple generations gathering to eat and laugh and sing. Our evolved social contract—to hunt, gather and farm collectively—tied us together, gave us our childhood and extended our golden years. Cooperative foraging also helped to fuel the cultural complexity and innovation that make birthdays and other rituals so fantastical and diverse. And at the center of it all is the universal commitment to share.

With eight billion humans on the planet today, one might begin to worry that we've taken things a bit too far. We've learned to turbocharge our energy budgets by tapping into climate-changing fossil fuels and flooding our world with cheap food. Calories are so easy to produce that very few of us spend our days foraging, a first in the history of life. This massive shift has been a boon to our collective creativity, enabling many to spend their lives as artists, doctors, teachers, scientists—a range of careers outside of food production. Having carved out our own strange niche, far removed from the laws that govern the rest of the natural world, we have only ourselves to look to for guidance. With a little luck and a lot of cooperation, we just might secure the human lineage another couple million birthdays. Make a wish. SA

FROM OUR ARCHIVES

Evolved to Exercise. Herman Pontzer; January 2019.

scientificamerican.com/magazine/sa

TWO NEUTRON STARS spiral toward an explosive collision. Recent evidence supports the theory that many of the periodic table's heavier elements form through such crashes.

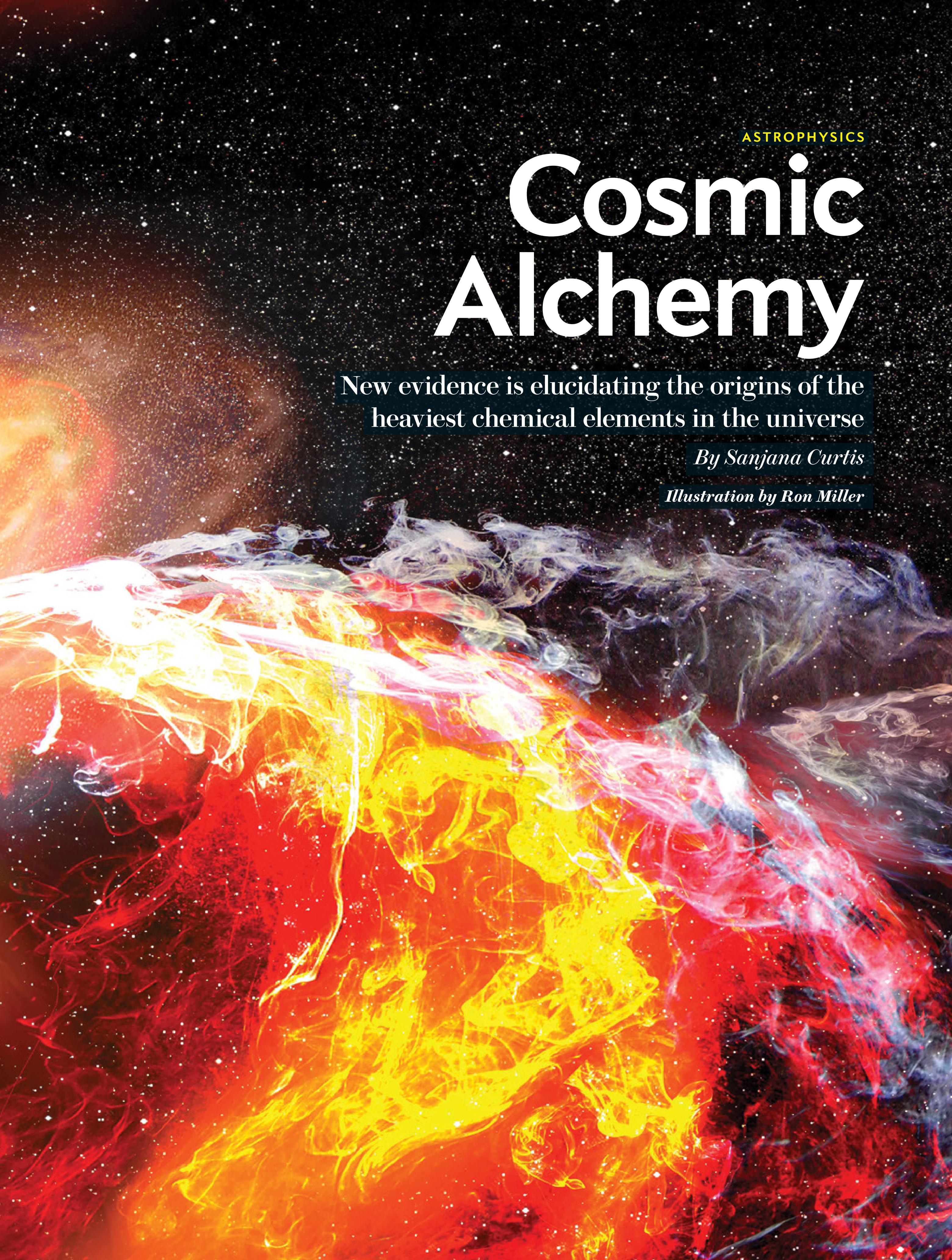
ASTROPHYSICS

Cosmic Alchemy

New evidence is elucidating the origins of the heaviest chemical elements in the universe

By Sanjana Curtis

Illustration by Ron Miller



Sanjana Curtis is a nuclear astrophysicist interested in the origin of elements and in multimessenger astronomy. She is a postdoctoral researcher at the University of Chicago's department of astronomy and astrophysics.

BITS OF THE STARS ARE ALL AROUND US, AND IN US, TOO. ABOUT HALF OF THE ABUNDANCE of elements heavier than iron originates in some of the most violent explosions in the cosmos. As the universe churns and new stars and planets form out of old gas and dust, these elements eventually make their way to Earth and other worlds. After 3.7 billion years of evolution on our planet, humans and many other species have come to rely on them in our bodies and our lives. Iodine, for instance, is a component of hormones we need to control our brain development and regulate our metabolism. Ocean microplankton called Acantharea use the element strontium to create intricate mineral skeletons. Gallium is critical for the chips in our smartphones and our laptop screens. And the mirrors of the JWST are gilded with gold, an element useful for its unreactive nature and ability to reflect infrared light (not to mention its popularity in jewelry).

Scientists have long had a basic idea of how these elements come to be, but for many years the details were hazy and fiercely debated. That changed recently when astronomers observed, for the first time, heavy-element synthesis in action. The process, the evidence suggests, went something like this.

Eons ago a star more than 10 times as massive as our sun died in a spectacular explosion, giving birth to one of the strangest objects in the universe: a neutron star. This newborn star was a remnant of the stellar core compressed to extreme densities where matter can take forms we do not understand. The neutron star might have cooled forever in the depths of space, and that would have been the end of its story. But most massive stars live in binary systems with a twin, and the same fate that befell our first star eventually came for its partner, leaving two neutron stars circling each other. In a dance that went on for millennia, the stars spiraled in, slowly at first and then rapidly. As they drew closer together, tidal forces began to rip them apart, flinging neutron-rich matter into space at velocities approaching one-third the speed of light. At last the stars merged, sending ripples through spacetime and setting off cosmic fireworks across the entire electromagnetic spectrum.

At the time of the crash, our own pale blue planet, in a quiet part of the Milky Way about 130 million light-years away, was home to the dinosaurs. The ripples in spacetime, called gravitational waves, began making their way across the cosmos, and in the time it took them to cover the vast distance to Earth, life on the planet changed beyond recognition. New species evolved and went extinct, civilizations rose and fell, and curious humans began looking up at the sky, developing instruments that could do incredible things such as measure minute distortions in spacetime. Eventually the gravitational waves (traveling at light speed) and the light from the merger reached Earth together. Astrophysicists recognized a distinctive glow that showed the presence of new elements. Humanity had just witnessed heavy-element production.

As an expert in cosmic cataclysms, I'm enthralled by both the science and the romance of this story—the creation of something new and enduring, even precious, from an ancient remnant of a once luminous star. And I'm thrilled that we finally get to see it happening. The discovery has answered several long-standing questions in astrophysics while also raising entirely new questions. But I and many scientists are energized. Our newfound ability to detect gravitational waves, as well as light from the same cosmic source, promises to help us understand astrophysical explosions and the synthesis of elements in a way that was previously impossible.

WE ARE STARDUST

THE QUEST to understand heavy-element formation is part of a larger scientific effort to answer a fundamental question: Where did everything come from? The cosmic history of the elements of the periodic table extends from a few minutes after the big bang to the present. The synthesis of the first elements—hydrogen, helium and lithium—occurred roughly three minutes after the birth of the universe. From these ingredients, the first stars formed, shining bright and fusing new elements in their cores during both their lives and their explosive deaths. The next generation of stars was born from the debris of these blasts, enriched with the elements formed by the first stars. This process continues today and accounts for all the elements from helium on the light end, with two protons per atom, all the way up to iron, which has 26 protons in its atomic nucleus. The heaviest elements, such as tennessine with 117 protons, aren't created by nature at all. But physicists can force them into being inside particle accelerators, where they typically last for mere thousandths of a second before decaying.

Several decades ago scientists theorized that about half of the elements heavier than iron are produced through a process called rapid neutron capture, or the r-process. The rest are thought to originate through slow neutron capture, or the s-process—a relatively well-understood sequence of reactions that occurs in long-lived, low-mass stars.

Both the r-process and the s-process involve adding one or more neutrons to an atomic nucleus. Adding neutrons, however, does not produce a new element, because elements are defined by the number of protons in their nucleus. What we do get is a heavier isotope of the same element—a nucleus containing the same number of protons but a different number of neutrons. This heavy isotope is often unstable and radioactive. Through what's called beta-minus decay, a neutron will transform into a proton, spitting out an electron and another subatomic particle called a neutrino in the process. In this way, the number of protons in an atom's nucleus increases, and a new element is born.

The key difference between the s-process and the r-process is speed. In the s-process, atoms capture neutrons slowly, and there is plenty of time for the newly added neutron to decay into a proton, creating the next stable element in the periodic table—with just one proton more—before another neutron comes along to be captured. This happens over thousands of years because there are only small numbers of extra neutrons lying around in the stars that host the s-process, so atoms are able to capture new neutrons only occasionally.

The r-process, in contrast, can produce the entire range of heavy elements in one spectacular flash of creation that barely lasts a second. In this scenario, neutrons are plentiful and slam into nuclei one after another before they have time to decay. A nucleus can rapidly balloon into a highly unstable isotope, going all the way up to what's called the neutron drip line—the absolute limit of the neutron-to-proton ratio allowed by nature inside a nucleus. The extremely heavy nucleus will then convert many of its neutrons to protons via beta decays or even break into smaller nuclei, ultimately producing a range of stable heavy elements. Many details about how this plays out are unclear. After a nucleus absorbs extra neutrons, for instance, but before it becomes stable, exotic nuclei arise that scientists don't understand. These in-between nuclei have properties that push the bounds of physics, and measuring them in a laboratory is difficult and sometimes even impossible.

Over the years scientists proposed many places in the universe where the r-process might occur, but the truth remained a mystery—among the greatest in nuclear astrophysics—for more than six decades. For a long time they thought core-collapse supernovae—explosive deaths of stars more than eight to 10 times the mass of our sun—might host the r-process. But simulations of typical core-collapse supernovae couldn't reproduce the neutron richness and thermodynamic conditions needed except, perhaps, in the case of rare explosions driven by strong magnetic fields. In 1974 James M. Lattimer and David N. Schramm suggested that decompressing neutron star matter could provide the ingredients for the r-process.

Over the years scientists proposed many places in the universe where the r-process might occur, but the truth remained a mystery.

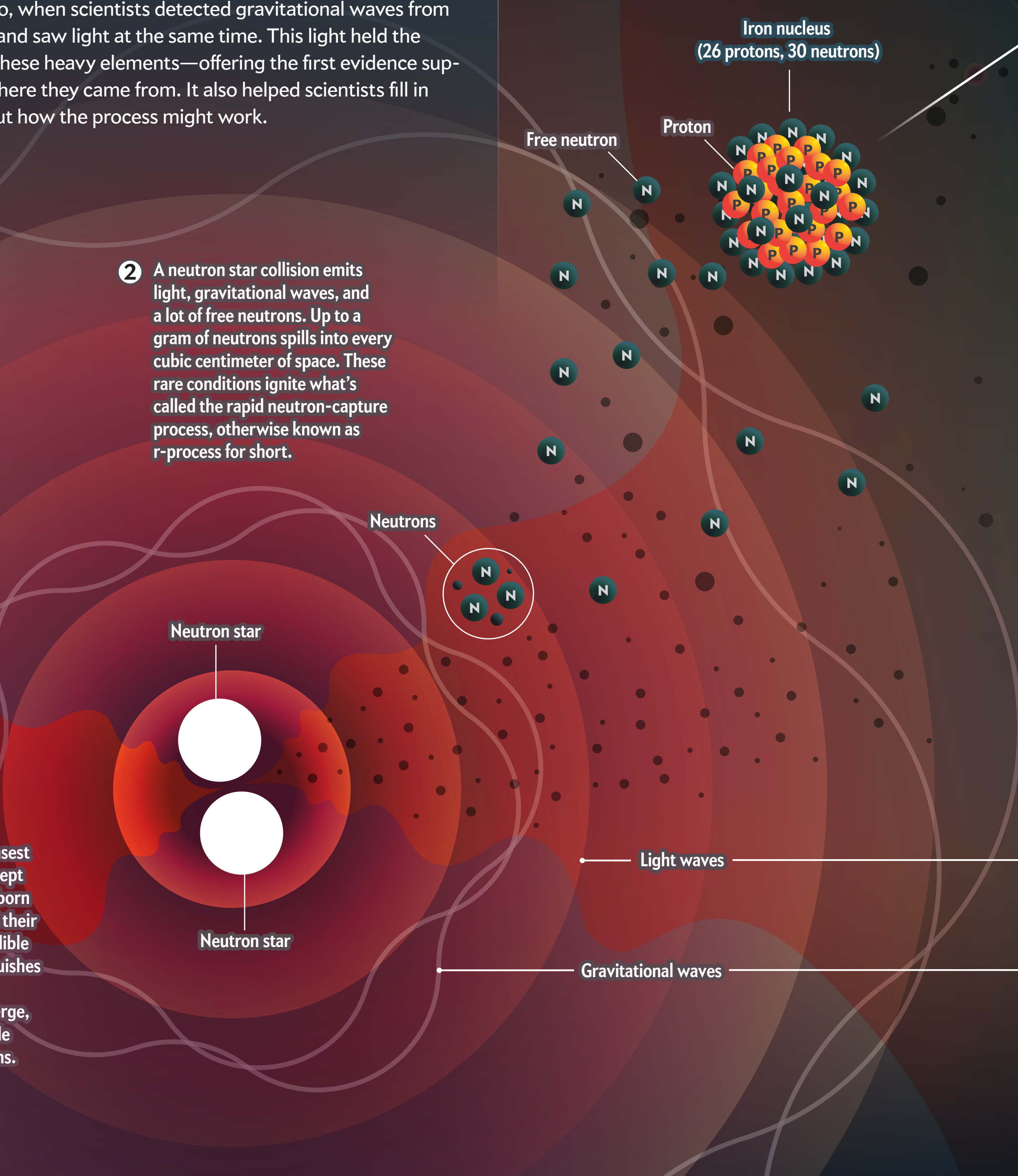
A neutron star is born when a massive star runs out of nuclear fuel and its gravity causes the core to collapse inward. The overwhelming force of the star's mass on the core compresses it to extremely high densities, causing electrons and protons to fuse together to become neutrons. While the rest of the star gets expelled in the supernova, the neutron star remains intact—a compact remnant containing the densest matter known in the universe. Neutron stars more massive than a certain limit further collapse into black holes, but we don't know the exact point of this transition, nor do we know how "squishy" they are. The inner structure of neutron stars is an open question. They might contain mostly neutrons and a small fraction of protons inside a crust of heavier nuclei at their surfaces. But their interiors could be even weirder than that. Deep inside the neutron star, matter may take on truly bizarre forms, ranging from a soup of quarks and gluons—the particles that make up normal matter—to a sea of "hyperons," which are made of so-called strange quarks.

Lattimer and Schramm proposed that neutron-rich matter is ejected when a neutron star collides with a black hole. But by 1982 scientists favored a scenario involving two neutron stars smashing together. While

How Heavy Elements Are Made

That ring on your finger made of platinum or gold contains a secret that has been at the center of a cosmic mystery. Scientists have been combing the galaxy to figure out where these so-called heavy elements come from. Lighter elements—everything from helium, with its two protons per atom, on up to iron, which has 26 protons in each nucleus—are better understood. Most of these form through nuclear fusion inside stars. But our knowledge gets fuzzy after iron. Gold, which has 79 protons in each atom, can't be made that way. The same goes for platinum, xenon, radon and many rare Earth elements.

For decades scientists debated where these heavy metals came from and how they arrived on Earth. The leading idea—the so-called rapid neutron-capture process triggered by an extremely violent cosmic event—is described below. Until recently, this was a theory with no observational backup. That changed a few years ago, when scientists detected gravitational waves from a neutron star collision and saw light at the same time. This light held the chemical signatures of these heavy elements—offering the first evidence supporting the theory of where they came from. It also helped scientists fill in some of the details about how the process might work.



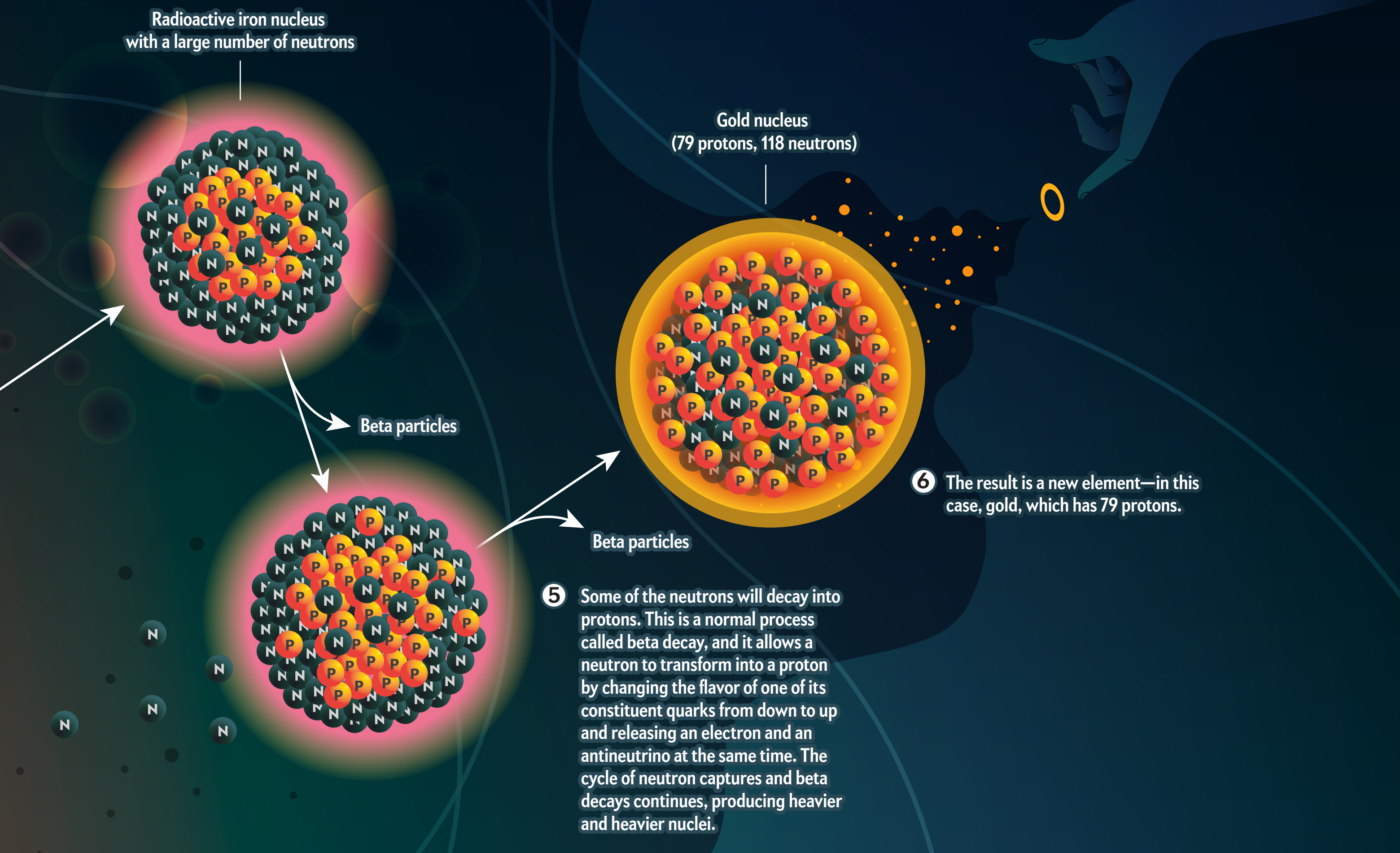
① Neutron stars are the densest things in the universe except for black holes. They are born when heavy stars die and their cores collapse. The incredible gravitational pressure squishes the atoms together, and protons and electrons merge, leaving behind a star made almost entirely of neutrons.

② A neutron star collision emits light, gravitational waves, and a lot of free neutrons. Up to a gram of neutrons spills into every cubic centimeter of space. These rare conditions ignite what's called the rapid neutron-capture process, otherwise known as r-process for short.

③ The r-process requires seed nuclei, such as that of iron, the heaviest element that can be formed from fusion inside stars. The iron nucleus begins with 26 protons and usually has around 30 neutrons. When bombarded with free neutrons, the nucleus captures many of them in a matter of milliseconds.

Graphic by Jason Drakeford

④ The new nucleus is extremely radioactive because of its lopsided number of neutrons.


Radioactive iron nucleus with a large number of neutrons
Beta particles
Gold nucleus (79 protons, 118 neutrons)
Beta particles
N
P

Just think—every time you wear a ring made of gold or platinum, you are holding a piece of the cosmos in your hand.

⑥ The result is a new element—in this case, gold, which has 79 protons.

⑤ Some of the neutrons will decay into protons. This is a normal process called beta decay, and it allows a neutron to transform into a proton by changing the flavor of one of its constituent quarks from down to up and releasing an electron and an antineutrino at the same time. The cycle of neutron captures and beta decays continues, producing heavier and heavier nuclei.

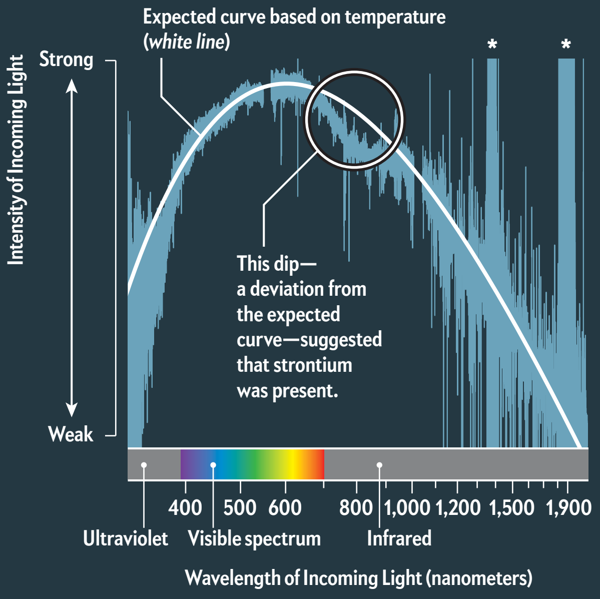
Light waves →

Gravitational waves →

DIRECT EVIDENCE

Scientists collected the first hard data supporting the r-process theory when gravitational waves and light from a neutron star collision were detected on Earth at the same time.

The light spectrum held the chemical signature of strontium (another heavy element), confirming that a heavy element was present in connection with the event that triggered the gravitational waves.



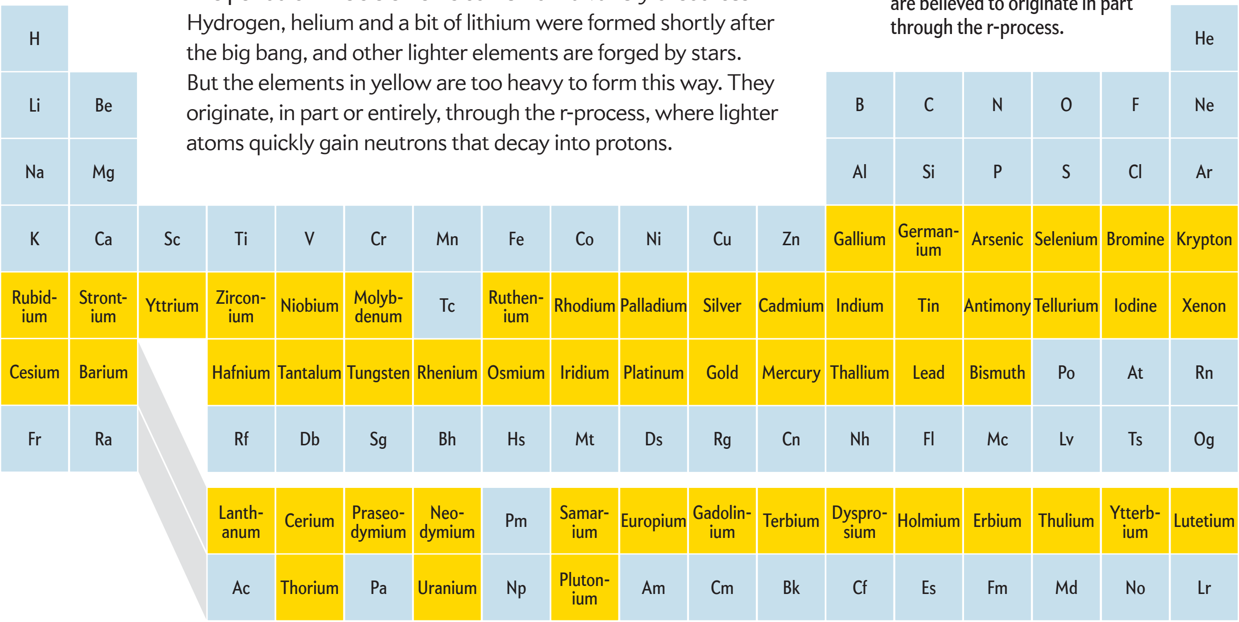
**Some wavelengths, including a few bands on the far right, are subject to known equipment calibration issues or atmospheric interference.*

Source: "Identification of Strontium in the Merger of Two Neutron Stars," by Darach Watson et al., arXiv:1910.10510; October 2019 (*chart reference*)

R-Process Elements

The periodic table's elements come from a variety of sources. Hydrogen, helium and a bit of lithium were formed shortly after the big bang, and other lighter elements are forged by stars. But the elements in yellow are too heavy to form this way. They originate, in part or entirely, through the r-process, where lighter atoms quickly gain neutrons that decay into protons.

● The highlighted elements, when found in the solar system, are believed to originate in part through the r-process.



H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Gallium	Germanium	Arsenic	Selenium	Bromine	Krypton
Rubidium	Strontium	Yttrium	Zirconium	Niobium	Molybdenum	Tc	Ruthenium	Rhodium	Palladium	Silver	Cadmium	Indium	Tin	Antimony	Tellurium	Iodine	Xenon
Cesium	Barium		Hafnium	Tantalum	Tungsten	Rhenium	Osmium	Iridium	Platinum	Gold	Mercury	Thallium	Lead	Bismuth	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
			Lanthanum	Cerium	Praseodymium	Neodymium	Pm	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium
			Ac	Thorium	Pa	Uranium	Np	Plutonium	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Sources: "Populating the Periodic Table: Nucleosynthesis of the Elements," by Jennifer A. Johnson, in *Science*, Vol. 363; February 2019; "Neutron-Capture Elements in the Early Galaxy," by Christopher Sneden et al., in *Annual Review of Astronomy and Astrophysics*, Vol. 46; 2008 *(reference)*

Graphic by Jen Christiansen

some researchers were working to understand how these crashes could synthesize new elements, others were trying to predict what kind of light we would expect to see from a neutron star merger. Some people suggested a connection between neutron star collisions and gamma-ray bursts—highly energetic explosions in space that emit a flash of gamma rays. And because r-process nuclei would be unstable and undergo radioactive decay, they should be able to heat up the material surrounding them and power an electromagnetic flare that would carry signatures of the elements produced. In 2010 Brian Metzger and his collaborators introduced the term "kilonova" to refer to such flares (first proposed in 1998) after determining that they would be approximately 1,000 times brighter than a regular flash of light called a nova.

Despite this intense theoretical development, there was little direct confirmation until just a few years ago, when one remarkable set of observations saw straight into the heart of a neutron star merger.

A COSMIC SYMPHONY

IN 2015 the Laser Interferometer Gravitational-wave Observatory (LIGO) did something extraordinary: it made the first observation of gravitational waves, which were generated by two black holes spiraling toward each other and merging. The detection was designated GW150914. At the time I was a graduate student at North Carolina State University. I remember watching the announcement along with the entire physics department in the common area of our building, feeling deeply moved. I tried to absorb everything I could about this new window to our universe. I learned that neutron star mergers produce less energy than black hole mergers, so they are more difficult to detect. But I and other scientists held out hope that soon the experiment would find them as well.

A couple of years passed, and LIGO and its sibling observatory Virgo detected more binary black hole collisions. Yet neutron star mergers remained elusive. Then, in the fall of 2017, I heard rumors that LIGO-Virgo had seen a neutron star collision for the first time. The rumors hinted that in addition to the gravitational-wave signal, astronomers had observed a short gamma-ray burst and something that looked a lot like a kilonova. The excitement among physicists was intense.

Soon enough, I was watching scientists from LIGO and various telescopes around the world announce the gravitational-wave observation, called GW170817, and the associated electromagnetic signals. I was awed by the amount of new knowledge these observations had already generated. The very next day there were almost 70 new papers about GW170817 on arXiv.org, a website where researchers can publish early, unreviewed versions of their papers. The event forecasted the promise of multimessenger astronomy—the ability to see cosmic phenomena through different "messengers" and combine the information to achieve a fuller understanding of the event. This was the first time astronomers saw gravitational waves and light—including radio, optical, x-ray and gamma-ray light—coming from the same celestial source.

The gravitational waves seen by LIGO-Virgo originated in the crash of a pair of neutron stars about 130 million light-years from Earth. This may seem far, but it's actually close for a gravitational-wave source. The details of the signal, such as how the waves' frequency and strength changed with time, allowed researchers to estimate that each neutron star had weighed about 1.17 to 1.6 times the mass of our sun and had a radius of roughly 11 to 12 kilometers.

As soon as the gravitational-wave signal arrived, astronomers followed up with conventional telescopes. Working together, LIGO and Virgo narrowed the location range for GW170817 to a much smaller region of the sky than in previous gravitational-wave events. Roughly 1.7 seconds after the gravitational waves came in, gamma-ray telescopes Fermi-GBM and INTEGRAL detected a faint burst of gamma rays lasting only a couple of seconds that came from the same direction as GW170817. This discovery definitively linked neutron star mergers with short gamma-ray bursts for the first time. But there was more! Images taken with the Henrietta Swopes one-meter telescope at the Las Campanas Observatory in Chile showed a new source of light located in the old but bright galaxy NGC 4993. By breaking up the light into its constituent colors and examining its spectrum, astronomers concluded that the signal was consistent with the idea that heavy elements were being forged there. We were looking at a true kilonova.

The way the kilonova's spectrum changed over time was interesting. Shorter wavelengths of light, which are bluer, peaked early, and longer, red wavelengths became predominant later. These peaks can be explained by the composition and velocity of the material ejected from the merger. A blue kilonova can be produced by fast-moving ejecta made mainly of lighter heavy elements without any "lanthanides"—the metallic periodic elements from lanthanum to lutetium, which are highly opaque to blue light. A red kilonova, in contrast, requires slow-moving ejecta containing lots of heavy elements, including lanthanides.

How does the merger generate these distinct components? This question puts us in uncertain territory, the realm of theory and simulations. Researchers are still trying to understand how the collision ejects material, what the material is made of and how the resulting kilonova unfolds. Kilonova spectra are very difficult to disentangle. Because the material is moving so fast, the fingerprints of various elements get smeared and blended together. We also lack reliable atomic data for many of the heavier elements, so it's hard to predict what their spectral signatures look like. The only plausible detection of an individual element in the GW170817 kilonova spectrum so far is of strontium. This is enough, though, to show that the r-process took place.

The discovery of this singular event has confirmed decades of theoretical predictions. Astrophysicists have finally established a connection between neutron star mergers and short gamma-ray bursts. The kilonova spectrum carries signatures of heavy elements, confirming that neutron star mergers are at least one site where r-process elements are produced.

But a lot remains to be understood and discovered. The mechanism that produces short gamma-ray bursts in mergers is still unclear. Properties of matter ejected in a merger are also changed in important ways by neutrinos. Careful tracking of these particles and their interactions in theoretical models is necessary but challenging and often requires a prohibitively large amount of computational power. We also don't know what object was created when the neutron stars merged. It could have been another neutron star, a neutron star on its way to becoming a black hole, or a black hole. Finally, although we now know that neutron star mergers can host the r-process, they are not the only places where it happens.

Observations of very old stars containing r-process elements suggest other possibilities, which include rare supernovae and collisions of neutron stars with black holes. We will not be able to uncover the origin of heavy elements with any one observation, no matter how extraordinary. GW170817 is just the beginning.

NEW OPPORTUNITIES

WE CAN'T EXPECT all kilonovae to look the same as the one associated with GW170817. We suspect they come in many forms, each with distinctive features, and we're in for a lot of surprises. In fact, astronomers at Northwestern University recently discovered a kilonova along with a long gamma-ray burst—an interesting combination suggesting that mergers can spawn gamma-ray bursts with longer light curves, too.

To understand the r-process, experts in several disciplines will have to work together: observational astronomers studying stars both old and new, gravitational-wave astronomers measuring distortions in spacetime, nuclear theorists constructing models of nuclear structures and of the matter inside neutron stars, experimental nuclear physicists tracking down the properties of unstable neutron-rich nuclei, and computational astrophysicists simulating events such as neutron star mergers by solving equations that take months to process on some of the largest computers in the world.

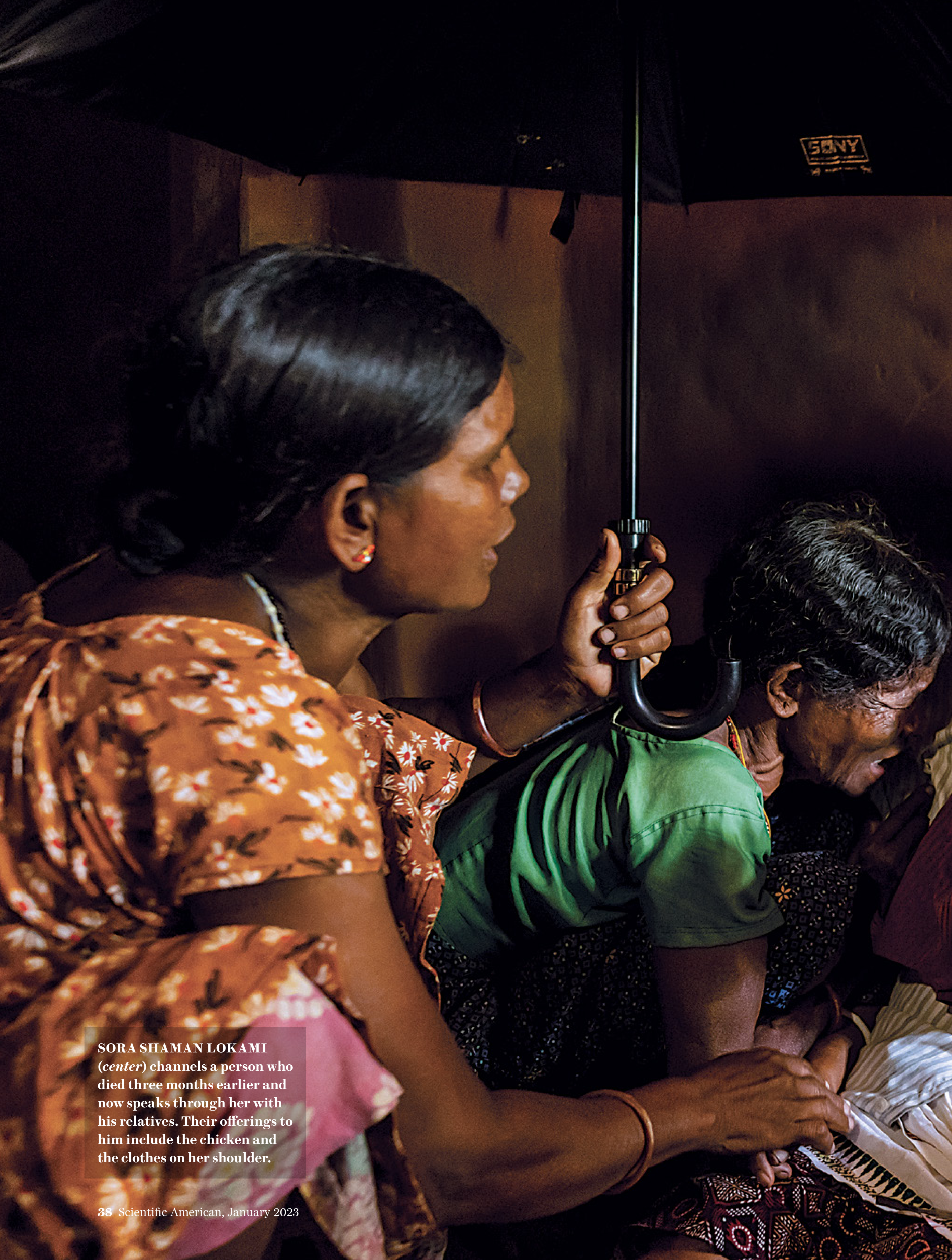
As existing gravitational-wave observatories become increasingly sensitive, new telescopes will come online to collect light from the transient sky. New projects such as the Facility for Rare Isotope Beams, which opened in May 2022 at Michigan State University, will measure the nuclear properties of rare nuclei. Proposed gravitational-wave observatories such as the ground-based Einstein Telescope are currently being planned in Europe.

Decades of progress in many fields have brought us to a point where we can investigate the origin of heavy elements in ways that were inaccessible just a few years ago. We are finally poised to put all the pieces together. Every isotope of every element in the periodic table has the potential to tell us something about the nuclear history of the universe. SA

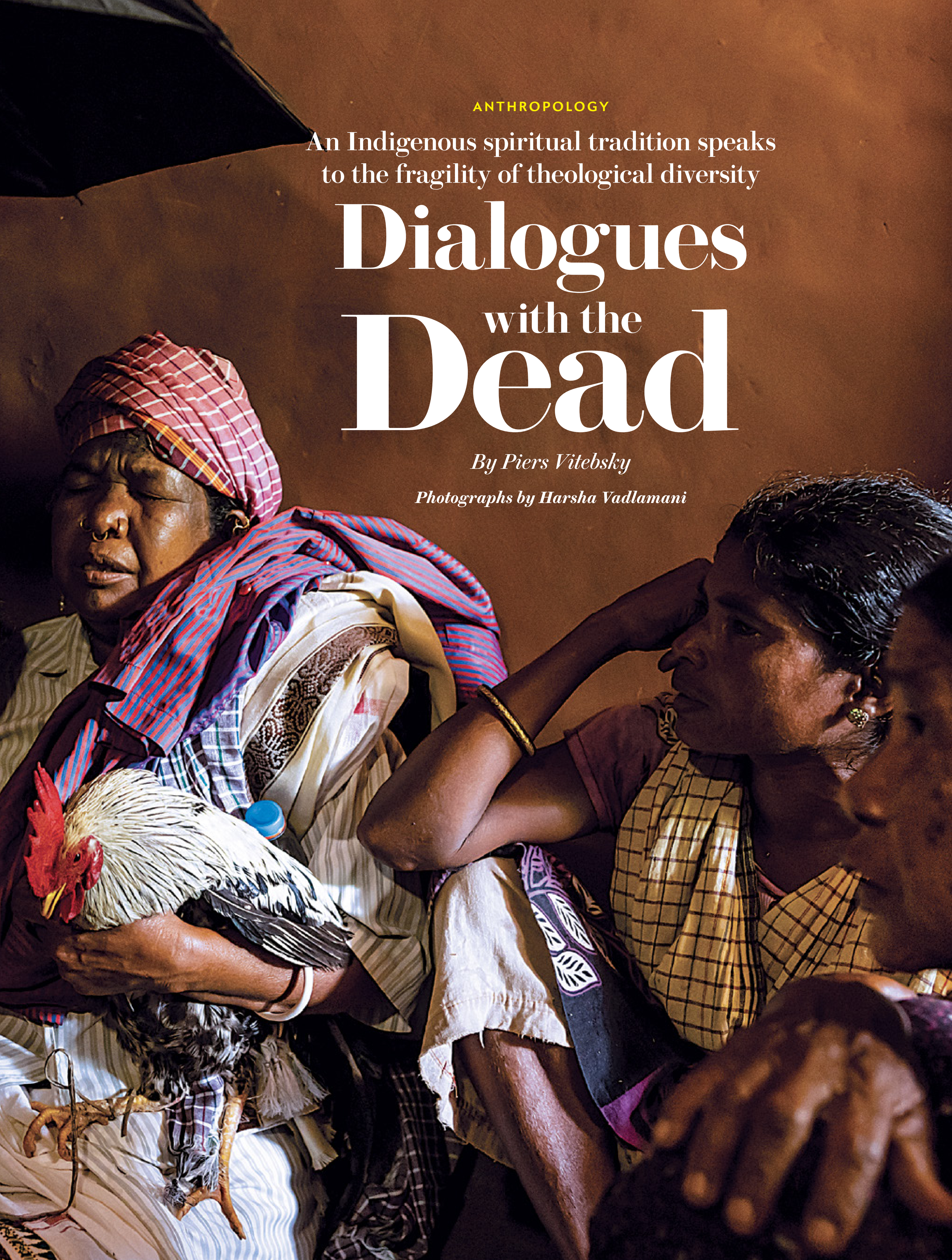
FROM OUR ARCHIVES

The Inner Lives of Neutron Stars. Clara Moskowitz; March 2019.

scientificamerican.com/magazine/sa



SORA SHAMAN LOKAMI (*center*) channels a person who died three months earlier and now speaks through her with his relatives. Their offerings to him include the chicken and the clothes on her shoulder.



ANTHROPOLOGY

An Indigenous spiritual tradition speaks to the fragility of theological diversity

Dialogues with the Dead

By Piers Vitebsky

Photographs by Harsha Vadlamani

Piers Vitebsky studies religion and ecology among Indigenous peoples of India and Siberia. He is emeritus head of anthropology and Russian northern studies at the Scott Polar Research Institute at the University of Cambridge and author of several books, including *Living without the Dead* (University of Chicago Press, 2017).

AT THE CORE OF RELIGIOUS wonder lies the mystery of life and death, and the world contains more understandings of this mystery than we can ever know. When I first stayed with the Sora Indigenous (or Adivasi) people in the highlands of Odisha, eastern India, as a graduate student in the 1970s, they engaged daily in conversations with their dead, who spoke through the mouths of shamans who were in a trance. Surrounded by shouting, drinking, and laughing dancers and musicians, living and dead Sora would gossip, cry and argue together for hours on end.

As a young Englishman clutching my notebook and tape recorder, I'd never imagined anything like it. What were the living and the dead saying to one another? What kind of magician was my new friend Ononti, the shaman with a spirit husband and children in the underworld—her relationship with them so intense that her marriage among the living had collapsed? What manner of skill enabled her to personify those the community had loved, the mourners embracing her stiff, entranced form in their desire to hold people who no longer had bodies of their own? What did she feel as she "became" one dead person after another? And what function did this elaborate ceremony serve?

My long, immersive visits over succeeding decades gradually revealed a worldview of extraordinary complexity, manifested in one of the most elaborate processes of grieving ever documented. The Sora religion I witnessed constituted not only a spiritual tradition but also a sophisticated system of psychotherapy and social regulation that consoled the bereaved, softened generational tensions, and subordinated ideological conflict to debate and compromise. Such Indigenous wisdoms around the world constitute a spiritual gene bank to fall back on as we become increasingly limited to the hegemonic belief systems of the present time.

I learned, too, that Indigenous cultures and spiritual traditions are tightly adapted to local social and historical conditions, which act like specialized ecological niches. This specificity gives them depth but also makes them vulnerable to uprooting and withering—a loss of what I call theodiversity as dramatic and potentially irreversible as any loss of biodiversity.

I was so engrossed in decoding the Sora worldview that I initially failed to notice that a new generation of Sora children, the first to attend school and become literate, was turning away from their ancestral religion toward Christian or, in some villages, Hindu sects. Young Sora, educated in a mainstream regional language, expressed contempt for the "backwardness" of their parents and grandparents—a contempt that often extended to me, as a sympathizer with the old religion. Now, almost half a century since I began my research, the traditional funeral rites are

AFTER THE TRANCE, **Lokami and the mourners sit outside the house where the ritual took place, stitching leaves from a sacred Sal tree into bowls for a sacrificial feast of chicken and rice.**

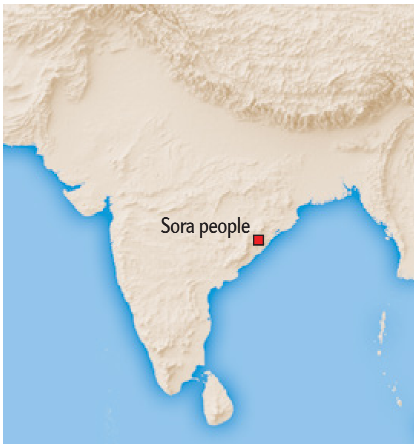
largely forgotten. Almost all the Sora who died during the COVID pandemic were given a Christian or Hindu funeral.

Our current age of mass extinction extends to a loss of cultural and religious diversity. These multiple, simultaneous losses are consequences of a monochromatic worldview that favors simple, overarching solutions over complex, multifaceted ones: monocrop plantations, economies based on single commodities, a global financial system, the imposition of majority languages in school and the rise of religious fundamentalisms. These parallels make it more pressing than ever for scholars to explore the diversity of human thinking, much of it among remote minority peoples, which is difficult to access and document, demands specialized research and is still largely unknown. Biology teaches us that diversity of forms in general enables adaptability and survival. The extinction of traditional Sora thought constitutes the loss of yet another species of theodiversity, a major resource for future-proofing a planet racked by contested histories, degraded environments, irresponsible governments and perpetual war.

In the new millennium, I was forced to turn my quest for understanding in an entirely new direction. If the world of the Sora shamans was as fulfilling as I had thought, why were so many younger Sora rejecting it so totally? The Sora, too, are reflecting on this change. Some of them are now asking for my field notes, photographs and tape recordings from the 1970s as heritage documentation of a culture they never experienced themselves, but the after-image of which continues to define their ethnic identity. And in accordance with the last wishes of my elderly Sora friend, Monosi, a Baptist modernizer who died in 2017, I am compiling a dictionary of the Sora language to present to the younger Sora, many of whom speak only Odia, the region's dominant language.

A CONSCIOUS WORLD

AT SCHOOL, I studied ancient Greek language and mythology, and I was fascinated by the ancient gods and spirits of the landscape. Living in modern Europe and surrounded by Christian and secular belief systems, I wondered: What would it feel like to live in an animistic world, where features of the environment like trees and rivers are believed to have humanlike consciousness? I could not live with the ancient Greeks, so I retrained as an anthropologist and searched the literature for surviving animistic cultures. I found an account of the Sora from the 1940s. These Adivasi communities lived by shifting cultivation of millets and other subsistence crops, as well as rice cultivation, in forested mountains of eastern India. They numbered some 400,000, spoke a language of the Austroasiatic family—unlike India's mainstream Indo-European and Dravidian languages—and lay largely outside the Hindu world. In January 1975, after three days' cycling from the regional capital and a further two days' walk along precarious mountain paths, I arrived in Rajingtal, a Sora village of about 600 people.



THE SORA Indigenous people live in the highlands of eastern India (*red*). Like many other Adivasis of the region, they speak an Austroasiatic language.

The Sora received me cautiously. Why should they welcome a stranger from a distant land who couldn't even speak their language? After two weeks I was able to join a band of men in their sessions of drinking the mildly fermented sap of the fishtail palm (*Caryota urens*). Eventually, after more weeks of testing and teasing, my first Sora friend, Inama, invited me to live with his family. He later gave me a separate house, but concerned that I'd be lonely, he also sent his little boy, Paranto, to keep me company. Paranto was often joined by his friends for a sleepover. The children's chatter hastened my learning of the Sora language while giving me inside access to village gossip.

Fieldwork in anthropology is like detective work: tactfully exploratory conversations, the dogged pursuit of clues, connections and patterns, the false starts and wonderful moments of illumination. Rajingtal's villagers helped me generously with food, water and firewood, and I joined in work parties and squatted among the people surrounding Ononti, observing her trances and her training of her designated successors: the teenage Taranti and the child Lokami. (Most Sora shamans were women, and their training began while they were little girls.) My quest was not just to learn *about* my Sora hosts but to learn something about the human condition *from* them.

I later lived in other Sora communities. Each village had several shamans, who specialized in various divinations, healings and funeral rites. Ononti, a small, forceful older woman, was one of the greatest. Sitting on the floor with legs outstretched, she would sing a rhythmic chant invoking her spirit husband and previous shamans—"Clasping hands, grandmothers, along the impossible tightrope path"—then enter a trance state as her soul descended to the underworld. This left her body "vacant" for 10 or 20 dead villagers to come up in succession to speak, each swigging palm wine through her mouth, discussing their family affairs and reproducing their own distinctive speech habits. I tried various tricks to test the extent to which shamans were consciously guiding these conversations, but they always remained in character. Despite decades of study, I never really understood the state of mind involved in a Sora shaman's trance—with its dreamlike nature, its blend of beauty and terror in the underworld, and the theatrical aspect of assuming one identity after another.

How could a people care so much about what happens to those they love after death? I wondered. And what induced them to come up with this particular solution to the problem of death—the concern of all religions? I came to realize that what my Sora friends feared most about death was not annihilation but separation from loved ones. In their view, a person who died didn't simply vanish but continued to exist and to feel—though not in any of the ways I'd ever thought about. The grief of this separation was felt equally keenly by both the living and the dead. So intense was this mutual attachment that the dead passed on the symptoms from which they themselves had suffered, bringing the living as close to them as they could. Indeed, for Sora, the only possible cause of illness and death was other dead people, in a literal interpretation of the consuming power of memory and grief. Physical and emotional pain were not separate—each illness was a reminder of your attachment to someone close to you who was now pulling you toward them by eating your soul.

And yet the living wanted to stay alive. The response to an illness was to give the dead the soul of a sacrificial animal as a substitute for your own and to engage the dead in conversation as they used the shaman's voice to explain their feelings in graphic detail. Here is Amboni, a young girl who died days earlier of leprosy, addressing, through the mouth of a shaman, her living mother, Rungkudi, and aunt, Sindi, in terms that surely aimed to give expression to their own feelings of guilt:

> **Amboni** (*arriving from the underworld, faintly*): Mummy, where are my gold nose rings?
> **Sindi**: They must have burned up in the pyre, darling. We looked but couldn't find them.
> **Amboni** (*petulantly*): Why don't you show me my nose rings?
> **Sindi**: They were so tiny. If I'd found them, of course I'd show them to you. Oh, my love, my darling, don't cause your own illness in others. Can you say that your mother and father didn't do enough sacrifices for you? They didn't turn their backs or refuse to help you, did they?...

Map by Mapping Specialists

DRINKING PALM WINE in the jungle at nightfall, Sora men dip a gourd into a communal pot and pass it from hand to hand. A thin stream of wine issues from a bamboo tube and a peacock quill and has to be aimed at the mouth.

Amboni (*addressing her silently weeping mother*): Mummy, you were horrid to me, you scolded me, you called me Scar-Girl, you called me Leper-Girl. You said, "You're a big girl now, why should I feed you when you sit around doing nothing?"
Sindi: She didn't mean it; she couldn't help saying it. You were growing up, and there were such a lot of chores to do.
Amboni (*sulkily*): I want my necklaces. Why can't I have my nose rings? I have to go digging, shoveling and leveling fields in the underworld, all without my nose rings. I came out in scars all over; my fingers started dropping off. That illness was passed on to me, that's how I got ill.
Sindi: But don't you pass it on. Don't give it to your mother and little sisters!
Amboni: If I grab them, I grab them. If I touch them, I touch them. If I pass it on, I pass it on: that's how it goes.
Sindi: Your cough, your choking, your scars, your wounds, don't pass them on!
Amboni (*calling back as she returns to the underworld*): My Mummy doesn't care enough about me!

In the first sessions after someone died, the dead person's feeling of victimhood prevailed, making them not only pitiable but also aggressive and dangerous. Over several years the living mourners persuaded the deceased into a less aggrieved state of mind. At successive stages of the funeral, the shaman's male assistants would sing and dance in the persona of the ancestors to "redeem" the newly dead person from the particular symptoms of their death and lead them into the company of their ancestors in the underworld.

Dialogues allowed the living and the dead to explore their shared life and now their separation and to heal each other's loss and resentments in a mutual bereavement therapy. This ancient recognition of the ambivalent feelings in any close relationship finds a striking echo in Sigmund's Freud's theory of bereavement, where a mourner may suffer from the same emotional condition as the deceased. But there is a crucial difference. Freud's psychological theory is individualistic: the memory of the dead person exists only in the mourner's mind. In contrast, the Sora conceived their dead as existing autonomously and reaching out to the living in a drama where relationships and feelings were not shut away in people's psyches but were performed in public for all to hear, see and debate. Death was not a lonely event; it was a shared condition.

In this highly social worldview, people are understood not so much as individuals as through their involvement with others. What we call the environment, too, is a socialized concept. The world was created in a mythic time by various local deities. Although the dead reside in an underworld, they are also distributed across the nearby landscape, where they infuse their soul force into the crops of their

descendants, reciprocating and recycling the vitality of the animal blood sacrificed to them by the living. This is not an exploitation of the earth, not even an ecologist's idea of stewardship; it is a cycle of total mutual nourishment and dependency. In this view, there is no impersonal "nature." Rather the very notion of environment is fully humanized through the dynamics of the memory traces that humans leave behind to be processed by shamans.

I also saw how the underworld reflected and inverted the power hierarchy in this world. My Sora friends were living at the tail end of a feudal regime that placed them in unremitting poverty and humiliation. Unable to read or to speak Odia, the Sora were forced to communicate with Odia-speaking police and other officials through a special caste of interpreters. Sora had no idea what was being said on their behalf or what officials were replying, and they were easy prey for systemic extortion, intimidation and fraud.

It turned out that the Sora shamans' spirit husbands, who enabled their entire technique of entering a trance, were themselves non-Adivasi police and government officers in the underworld! They were fantasy counterparts of the very people who oppressed the Sora aboveground, but within this fantasy they were domesticated by the shamans through marriage. The shamans' spirit husbands could speak Odia as they "wrote down" the names of the ancestors of the shamans' clients. They commanded the mysterious and powerful technique of writing but used it not to persecute the Sora but to open a channel to their ancestors.

Two years after my first encounter with Ononti, and by then living in a neighboring village, Sogad, I became one of these funeral assistants singing the songs that supported the shamans' trances. By now I had learned to transcribe and translate dialogues between the living and dead and noticed an evolution in their emotional tone. These dialogues were a method for crafting the disordered and distressing fading of memory into a structured and healthy forgetting. Conversations with people who had died recently were full of intense anguish, of love and longing mixed with guilt, as the dead accused the living of neglect while the living defended themselves. As the tone became more relaxed over the years, the grief diminished on both sides and the dead person became less likely to be diagnosed as the cause of illness or death. Eventually, as they evolved from predator into protector, the dead gave their personal name back to a baby among their living relatives.

And finally, as I worked out by tracing genealogies, when nobody was left alive to remember them, the dead person turned into a butterfly, a memory without a rememberer. This was the true end of the person, the final resolution of their suffering and that of those attached to them.

GLOBAL RELIGIONS

MY YOUTHFUL RESEARCH was completed by the 1980s and encapsulated in my first book on the Sora, but I continued to visit my friends. The shamanic tradition was fading as mainstream religions advanced. But what I saw as loss, young Sora were seeing as liberation. Canadian Baptist missionaries had been offering Christianity to the local populace for decades, moving up from an original base in the plains to one on the other side of the Sora

hills from Rajingtal and Sogad. The foreign missionaries left under government pressure in the 1970s, but their vigorous core of Sora converts continued to advance their religion into the remotest uphill villages. The church adapted the Roman alphabet to introduce literacy in the Sora language, and in the 1980s a flood of government schools, roads, employment and development cash introduced speaking and writing in Odia, too. Between them, church and school completely undid the Sora's previous exploitation and created a more confident and prosperous new generation.

The great shaman Ononti gave up trancing in the early 1990s, heartbroken by the death of Maianti, a dear friend and colleague, and shocked by the disrespect of some Sora youths, who had torn off her gold necklace. She died in 2005.

One chilly December night a few months after Ononti's death, five women shamans, including Ononti's former pupils Lokami and Taranti, sat side by side and started to enter a trance, their souls descending into the underworld to meet their spirit husbands and children, and to bring up a succession of ancestors to talk with their descendants and mourners. The spirit of Ononti came back to greet me through Lokami's mouth and joke about our adventures together. But suddenly, Taranti fell out of her trance—something I'd never seen before—and started weeping, "Why can't I do it? I was terrified on the path, I came back, I woke up. Will I never see my family in the underworld again?"

I knew Taranti's children in the world of the living. They had become officials in the Baptist Church, and her profession—witchcraft, to Baptist eyes—was damaging their chances of promotion. Now, under the pressure of their repeated shaming, she'd lost her confidence. I felt for my friend's anguish and wondered all the more about the reason for young people's conversion. As a social scientist, I couldn't simply accept the Christians' own explanation: because they are right. I had to find a social interpretation.

All religions acknowledge suffering as an inherent and unavoidable part of the human condition, and all offer some form of hope and liberation. But a new religion also changes one's fundamental understanding of the universe. The underworld of the dead was now counterbalanced by a new idea of heaven. "I don't know if I'll go to the sky or the underworld when I die," one old man told me. "But I prefer the underworld—the company's better there!"

To my understanding, the deepest change was in the relationship between living and dead. For Sora Baptists, death comes about through the "will of God"—a motivation they still find hard to explain. Lengthy shamanic dialogues, which reinforced attachment to the dead, are now replaced by a brief, final funeral and an attachment of a new kind, to a new and distant deity and his son Jesus.

Whereas prolonged interaction with the dead brought animists solace, Sora Baptists feel better by severing all contact. "Remembering makes you ill," a young Christian told me simply. Indeed,

MAINSTREAM RELIGIONS, in particular, Hinduism and Christianity, are replacing the Sora belief system. Sora men build a chariot to the Hindu god Jagannath (*left*); Sora women pray in a Baptist church to a distant god (*right*).

AN EARTH SPIRIT lives in the rock where Lokami stands. Earth spirits symbolize water and the principle of wholeness, reuniting ancestors split apart by diverse experiences of death.

local Baptist ideology aims for complete rupture not only with the dead but also with the old religion, which, the Sora pastors insist, must be abandoned entirely. And although younger people feel liberated as they become literate in both Sora and Odia and give up subsistence agriculture and "primitive" customs to join the mainstream competition for jobs, older Sora with the traditional worldview have a new reason to fear death: "You've seen how I talk to my dead parents, but after I die, will my children talk to me?"

One can be caught between these worldviews. My old friend Inama died around 1992. His son Paranto, now an adult and Baptist convert, gave him a minimalist Christian funeral. But Paranto had started life as an animist and now had difficulty finding a way to mourn his dead father. "I met my father in a dream," he told me several years later. "It was as if we were meeting in waking life:

> 'You've died—where have you come from?' I asked.
> 'I'm not dead,' my father said. 'I remain, I exist.'
> "I got up and looked around: it was the middle of the night—there was nobody there! I cried. I was very sad.
> 'I thought you were dead!' I said. I met him on the way to his favorite drinking place. 'Ai! Where are you going?'
> 'I'm just wandering around.' He looked just as he had when he was healthy.
> 'But how come your body was so sick, and now you're healthy again?'
> 'It's all right. I'm fine now.'

“I looked around; there was nobody. He didn’t harm me. We just talked and cried together.”

Through this dream, Paranto received a reassurance about his father’s well-being that the old religion had offered but Christianity cannot give. He was forbidden to speak with his dead father through a shaman, but the dream subverted this prohibition by re-creating an entire dialogue between them.

Even fervent converts can find themselves conflicted. My friend Monosi had become one of the very first Sora Baptists in the 1940s. He traveled throughout India on church business and helped with Bible translation. In the mid-1970s I hesitated to approach him because I assumed he would disapprove of my interests. But one day in 1977 I asked him to help me understand a tape of chants by Ononti’s young apprentice Taranti. Monosi became enchanted with an exquisite incantation she’d sung while in trance in the persona of a peacock spirit, naming each place as it flew across the landscape. This epiphany changed Monosi’s life. He begged me to bring him more tapes and started accompanying me to rituals, his eyes opened to a world he had once rejected—thereby earning severe disapproval from the Sora Baptist pastors.

Over 30 years later, in a mood of partial regret, Monosi collaborated with me in 2011 to compile shamanic texts and archival photos, to document the culture he had done so much to change. Now avidly read by young Sora, this book about their own ancestral history is the main book available in Sora apart from the Bible.

If, as these encounters suggested, Christianity did not offer a more comforting view of life, death and suffering, what did it offer that was so attractive to the younger Sora? One clue was that Sora in some other areas were also converting—but to orthodox strands of Hinduism, influenced by Hindu missionaries who claim that India’s Adivasis are really Hindus who lost contact with proper Hinduism in the jungle. These missionaries don’t reject Adivasi religions but seek to clean them up by abolishing “bad” habits such as animal sacrifice. But even though Christianity seeks rupture and Hinduism seeks reform, sociologically they are functional equivalents: both offer a similar pathway for coming out of isolation and reinforce the impact of schools, roads and jobs by drawing the Sora more directly into the Indian mainstream.

These new religions are more appropriate to the new circumstances in which younger Sora find themselves. As they abandon jungle slopes with their subsistence crops, newly literate Sora are streaming downhill to integrate into the Indian nation-state and the wider global world. The geographies of Christianity and Hinduism are not oriented to features of the local environment but to biblical Israel, where no Sora has ever been, or the sacred sites of Hindu nationalism. In abandoning their ancestors and turning to Jesus or Krishna, young Sora are not so much converting *to* new religious forms but rather *away from* their previous isolation and poverty.

History recounts many instances of conversion from local to world religions. In Europe, this transition from “paganism” took many centuries and has never been fully completed. My life with the Sora has shown me the dislocation and pain that these streamlined accounts mask. At the same time as young Sora are achieving political and economic emancipation, they pay a high psychological price as they lose intimate bonds with their ancestors and environment. Taranti’s sundering from her beloved spirit family and Paranto’s inability to speak to his dead father in waking life are just single moments of personal drama in a vast historical shift.

It is true that the Sora are now less exploited and impoverished than before. But they are also more likely to be drawn into the culture wars grounded in depersonalized, delocalized ideologies that are ripping the world apart, in India as much as in Euro-America. Taranti’s tears at her lost world, Monosi’s theological agonizing, and Paranto’s comforting dream should concern us all. SA

FROM OUR ARCHIVES

Designing for Life. Carolina Schneider Comandulli; May 2022.

scientificamerican.com/magazine/sa

The Universe Is Not Locally Real

QUANTUM PHYSICS

Experiments with entangled light have revealed a profound mystery at the heart of reality

By Daniel Garisto

Daniel Garisto is a freelance science journalist covering advances in physics and other natural sciences. He is based in New York.

ONE OF THE MORE UNSETTLING DISCOVERIES IN THE PAST HALF A CENTURY is that the universe is not locally real. In this context, “real” means that objects have definite properties independent of observation—an apple can be red even when no one is looking. “Local” means that objects can be influenced only by their surroundings and that any influence cannot travel faster than light. Investigations at the frontiers of quantum physics have found that these things cannot both be true. Instead the evidence shows that objects are *not* influenced solely by their surroundings, and they *may* also lack definite properties prior to measurement.

This is, of course, deeply contrary to our everyday experiences. As Albert Einstein once bemoaned to a friend, “Do you really believe the moon is not there when you are not looking at it?” To adapt a phrase from author Douglas Adams, the demise of local realism has made a lot of people very angry and has been widely regarded as a bad move.

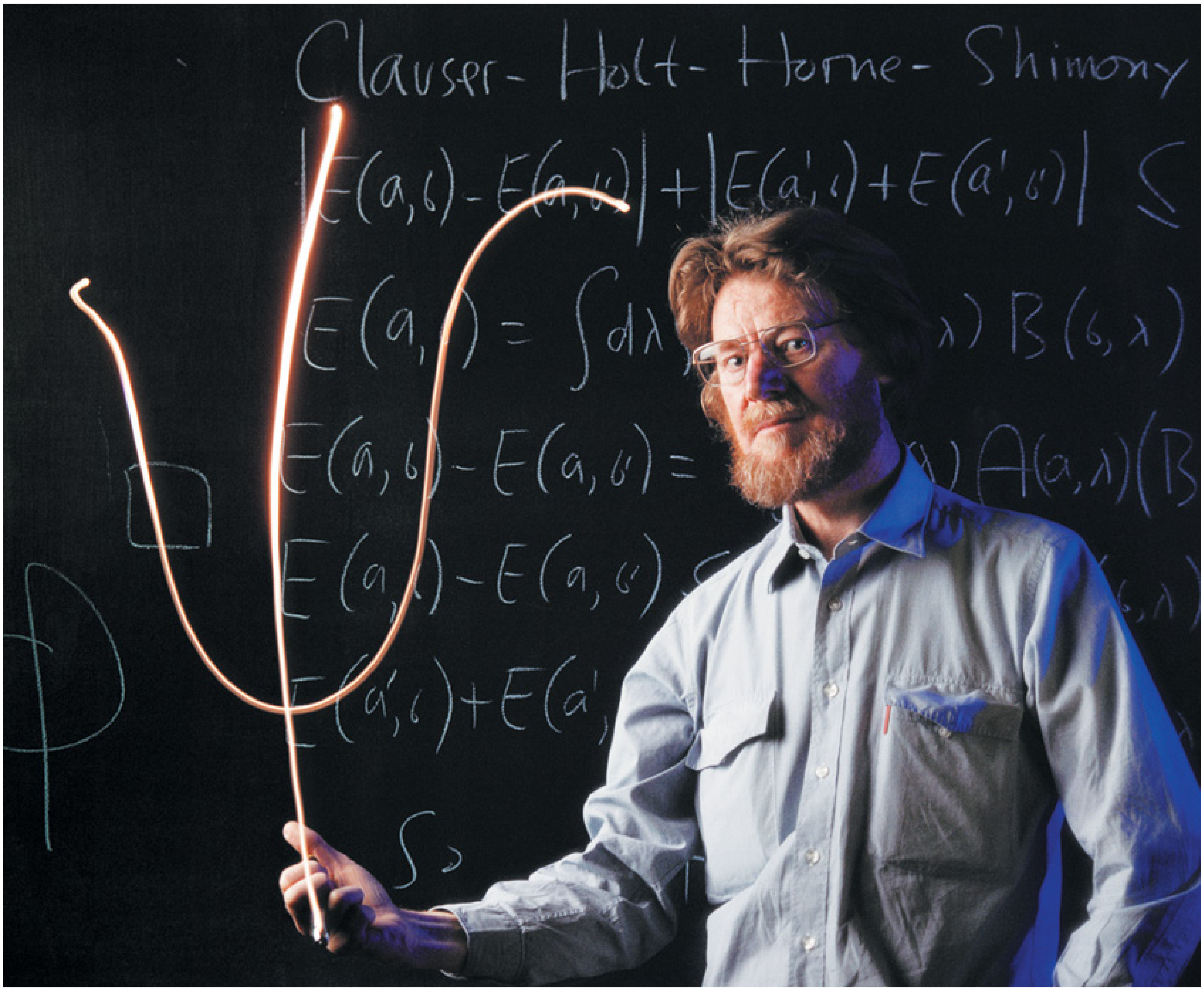
Blame for this achievement has now been laid squarely on the shoulders of three physicists: John Clauser, Alain Aspect and Anton Zeilinger. They equally split the 2022 Nobel Prize in Physics “for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science.” (“Bell inequalities” refers to the pioneering work of Northern Ireland physicist John Stewart Bell, who laid the foundations for the 2022 Physics Nobel in the early 1960s.) Colleagues agreed that the trio had it coming, deserving this reckoning for overthrowing reality as we know it. “It was long overdue,” says Sandu Popescu, a quantum physicist at the University of Bristol in England. “Without any doubt, the prize is well deserved.”

“The experiments beginning with the earliest one of Clauser and continuing along show that this stuff isn’t just philosophical, it’s real—and like other real things, potentially useful,” says Charles Bennett, an eminent quantum researcher at IBM. “Each year I thought, ‘Oh, maybe this is the year,’ ” says David Kaiser, a physicist and historian at the Massachusetts Institute of Technology. “This year it really was. It was very emotional—and very thrilling.”

The journey from fringe to favor was a long one. From about 1940 until as late as 1990, studies of so-called quantum foundations were often treated as philosophy at best and crackpottery at worst. Many scientific journals refused to publish papers on the topic, and academic positions indulging such investigations were nearly impossible to come by. In 1985 Popescu’s adviser warned him against a Ph.D. in the subject. “He said, ‘Look, if you do that, you will have fun for five years, and then you will be jobless,’ ” Popescu says.

Today quantum information science is among the most vibrant subfields in all of physics. It links Einstein’s general theory of relativity with quantum mechanics via the still mysterious behavior of black holes. It dictates the design and function of quantum sensors, which are increasingly being used to study everything from earthquakes to dark matter. And it clarifies the often confusing nature of quantum entanglement, a phenomenon that is pivotal to modern materials science and that lies at the heart of quantum

Athul Satheesh/500px/Getty Images (*preceding pages*)



JOHN STEWART BELL'S work in the 1960s sparked a quiet revolution in quantum physics.

Peter Menzel/Science Source

computing. "What even makes a quantum computer 'quantum?'" Nicole Yunger Halpern, a National Institute of Standards and Technology physicist, asks rhetorically. "One of the most popular answers is entanglement, and the main reason why we understand entanglement is the grand work participated in by Bell and these Nobel Prize winners. Without that understanding of entanglement, we probably wouldn't be able to realize quantum computers."

FOR WHOM THE BELL TOLLS

THE TROUBLE WITH quantum mechanics was never that it made the wrong predictions—in fact, the theory described the microscopic world splendidly right from the start when physicists devised it in the opening decades of the 20th century. What Einstein, Boris Podolsky and Nathan Rosen took issue with, as they explained in their iconic 1935 paper, was the theory's uncomfortable implications for reality. Their analysis, known by their initials EPR, centered on a thought experiment meant to illustrate the absurdity of quantum mechanics. The goal was to show how under certain conditions the theory can break—or at least deliver nonsensical results that conflict with our deepest assumptions about reality.

A simplified and modernized version of EPR goes something like this: Pairs of particles are sent off in different directions from a common source, targeted for two observers, Alice and Bob, each stationed at opposite ends of the solar system. Quantum mechanics dictates that it is impossible to know the spin, a quantum property of individual particles, prior to measurement. Once Alice measures one of her particles, she finds its spin to be either "up" or "down. " Her results are random, and yet when she measures up, she instantly knows that Bob's corresponding particle—which had a random, indefinite spin—must now be down. At first glance, this is not so odd. Maybe the particles are like a pair of socks—if Alice gets the right sock, Bob must have the left.

But under quantum mechanics, particles are not like socks, and only when measured do they settle on a spin of up or down. This is EPR's key conundrum: If Alice's particles lack a spin until measurement, then how (as they whiz past Neptune) do they know what Bob's particles will do as they fly out of the solar system in the other direction? Each time Alice measures, she quizzes her particle on what Bob will get if he flips a coin: up or down? The odds of correctly predicting this even 200 times in a row are one in 10^{60}—a number greater than all the atoms in the solar system. Yet despite the billions of kilometers that separate the particle pairs, quantum mechanics says Alice's particles can keep correctly predicting, as though they were telepathically connected to Bob's particles.

Designed to reveal the incompleteness of quantum mechanics, EPR eventually led to experimental results that instead reinforce the theory's most mind-boggling tenets. Under quantum mechanics, nature is not locally real: particles may lack properties such as spin up or spin down prior to measurement, and they seem to talk to one another no matter the distance. (Because the outcomes of measurements are random, these correlations cannot be used for faster-than-light communication.)

Physicists skeptical of quantum mechanics proposed that this puzzle could be explained by hidden variables, factors that existed in some imperceptible level of reality, beneath the subatomic realm, that contained information about a particle's future state. They hoped that in hidden variable theories, nature could recover the local realism denied it by quantum mechanics. "One would have thought that the arguments of Einstein, Podolsky and Rosen would produce a revolution at that moment, and everybody would have started working on hidden variables," Popescu says.

Einstein's "attack" on quantum mechanics, however, did not catch on among physicists, who by and large accepted quantum mechanics as is. This was less a thoughtful embrace of nonlocal reality than a desire not to think too hard—a head-in-the-sand sentiment later summarized by American physicist N. David Mermin as a demand to "shut up and calculate." The lack of interest was driven in part because John von Neumann, a highly regarded scientist, had in 1932 published a mathematical proof ruling out hidden variable theories. Von Neumann's proof, it must be said, was refuted just three years later by a young female mathematician, Grete Hermann, but at the time no one seemed to notice.

The problem of nonlocal realism would languish for another three decades before being shattered by Bell. From the start of his career, Bell was bothered by quantum orthodoxy and sympathetic toward hidden variable theories. Inspiration struck him in 1952, when he learned that American physicist David Bohm had formulated a viable nonlocal hidden variable interpretation of quantum mechanics—something von Neumann had claimed was impossible.

Bell mulled the ideas for years, as a side project to his job working as a particle physicist at CERN near Geneva. In 1964 he rediscovered the same flaws in von Neumann's argument that Hermann had. And then, in a triumph of rigorous thinking, Bell concocted a theorem that dragged the question of local hidden variables from its metaphysical quagmire onto the concrete ground of experiment.

Typically local hidden variable theories and quantum mechanics predict indistinguishable experimental outcomes. What Bell realized is that under precise circumstances, an empirical discrepancy between the two can emerge. In the eponymous Bell test (an evolution of the EPR thought experiment), Alice and Bob receive the same paired particles, but now they each have two different detector settings—A and a, B and b. These detector settings are an additional trick to throw off Alice and Bob's apparent telepathy. In local hidden variable theories, one particle cannot know which question the other is asked. Their correlation is secretly set ahead of time and is not sensitive to updated detector settings. But according to quantum mechanics, when Alice and Bob use the same settings (both uppercase or both lowercase), each particle is aware of the question the other is posed, and the two will correlate perfectly—in sync in a way no local theory can account for. They are, in a word, entangled.

Measuring the correlation multiple times for many particle pairs, therefore, could prove which theory was correct. If the correlation remained below a limit derived from Bell's theorem, this would suggest hidden variables were real; if it exceeded Bell's limit, then the mind-boggling tenets of quantum mechanics would reign supreme. And yet, in spite of its potential to help determine the nature of reality, Bell's theorem languished unnoticed in a relatively obscure journal for years.

THE BELL TOLLS FOR THEE

IN 1967, A GRADUATE STUDENT at Columbia University named John Clauser accidentally stumbled across a library copy of Bell's paper and became enthralled by the possibility of proving hidden variable theories correct. When Clauser wrote to Bell two years later, asking if anyone had performed the test, it was among the first feedback Bell had received.

Three years after that, with Bell's encouragement, Clauser and his graduate student Stuart Freedman performed the first Bell test. Clauser had secured permission from his supervisors but little in the way of funds, so he became, as he said in a later interview, adept at "dumpster diving" to secure equipment—some of which he and Freedman then duct-taped together. In Clauser's setup—a kayak-sized apparatus requiring careful tuning by hand—pairs of photons were sent in opposite directions toward detectors that could measure their state, or polarization.

Unfortunately for Clauser and his infatuation with hidden variables, once he and Freedman completed their analysis, they had to conclude that they had found strong evidence against them. Still, the result was hardly conclusive because of various "loopholes" in the experiment that conceivably could allow the influence of hidden variables to slip through undetected. The most concerning of these was the locality loophole: if either the photon source or the detectors could have somehow shared information (which was plausible within an object the size of a kayak), the resulting measured correlations could still emerge from hidden variables. As David Kaiser explained, if Alice tweets at Bob to tell him her detector setting, that interference makes ruling out hidden variables impossible.

Closing the locality loophole is easier said than done. The detector setting must be quickly changed while photons are on the fly—"quickly" meaning in a matter of mere nanoseconds. In 1976 a young French expert in optics, Alain Aspect, proposed a way for doing this ultra-speedy switch. His group's experimental results, published in 1982, only bolstered Clauser's results: local hidden variables looked extremely unlikely. "Perhaps Nature is not so queer as quantum mechanics," Bell wrote in response to Aspect's test. "But the experimental situation is not very encouraging from this point of view."

Other loopholes remained, however, and Bell died in 1990 without witnessing their closure. Even Aspect's experiment hadn't fully ruled out local effects, because it took place over too small a distance. Similarly, as Clauser and others had realized, if Alice and Bob detected an unrepresentative sample of particles—like a survey that contacted only right-handed people—their experiments could reach the wrong conclusions.

No one pounced to close these loopholes with more gusto than Anton Zeilinger, an ambitious, gregarious Austrian physicist. In 1997 he and his team improved on Aspect's earlier work by conducting a Bell test over a then unprecedented distance of nearly half a kilometer. The era of divining reality's nonlocality from kayak-sized experiments had drawn to a close. Finally, in 2013, Zeilinger's group took the next logical step, tackling multiple loopholes at the same time.

"Before quantum mechanics, I actually was interested in engineering. I like building things with my hands," says Marissa Giustina, a quantum researcher at Google who worked with Zeilinger. "In retrospect, a loophole-free Bell experiment is a giant systems-engineering project." One requirement for creating an experiment closing multiple loopholes was finding a perfectly straight, unoccupied 60-meter tunnel with access to fiber-optic cables. As it turned out, the dungeon of Vienna's Hofburg palace was an almost ideal setting—aside from being caked with a century's worth of dust. Their results, published in 2015, coincided with similar tests from two other groups that also found quantum mechanics as flawless as ever.

BELL'S TEST REACHES THE STARS

ONE GREAT FINAL LOOPHOLE remained to be closed—or at least narrowed. Any prior physical connection between components, no matter how distant in the past, has the possibility of interfering with the validity of a Bell test's results. If Alice shakes Bob's hand prior to departing on a spaceship, they share a past. It is seemingly implausible that a local hidden variable theory would exploit these loopholes, but it was still possible.

In 2016 a team that included Kaiser and Zeilinger performed a cosmic Bell test. Using telescopes in the Canary Islands, the researchers sourced its random decisions for detector settings from stars sufficiently far apart in the sky that light from one would not reach the other for hundreds of years, ensuring a centuries-spanning gap in their shared cosmic past. Yet even then, quantum mechanics again proved triumphant.

One of the principal difficulties in explaining the importance of Bell tests to the public—as well as to skeptical physicists—is the perception that the veracity of quantum mechanics was a foregone conclusion. After all, researchers have measured many key aspects of quantum mechanics to a precision of greater than 10 parts in a billion. "I actually didn't want to work on it," Giustina says. "I thought, like, 'Come on, this is old physics. We all know what's going to happen.'" But the accuracy of quantum mechanics could not rule out the possibility of local hidden variables; only Bell tests could do that.

Today quantum information science is among the most vibrant subfields in all of physics.

"What drew each of these Nobel recipients to the topic, and what drew John Bell himself to the topic, was indeed [the question], 'Can the world work that way?'" Kaiser says. "And how do we really know with confidence?" What Bell tests allow physicists to do is remove the bias of anthropocentric aesthetic judgments from the equation. They purge from their work the parts of human cognition that recoil at the possibility of eerily inexplicable entanglement or that scoff at hidden variable theories as just more debates over how many angels may dance on the head of a pin.

The award honors Clauser, Aspect and Zeilinger, but it is testament to all the researchers who were unsatisfied with superficial explanations about quantum mechanics and who asked their questions even when doing so was unpopular. "Bell tests," Giustina concludes, "are a very useful way of looking at reality." SA

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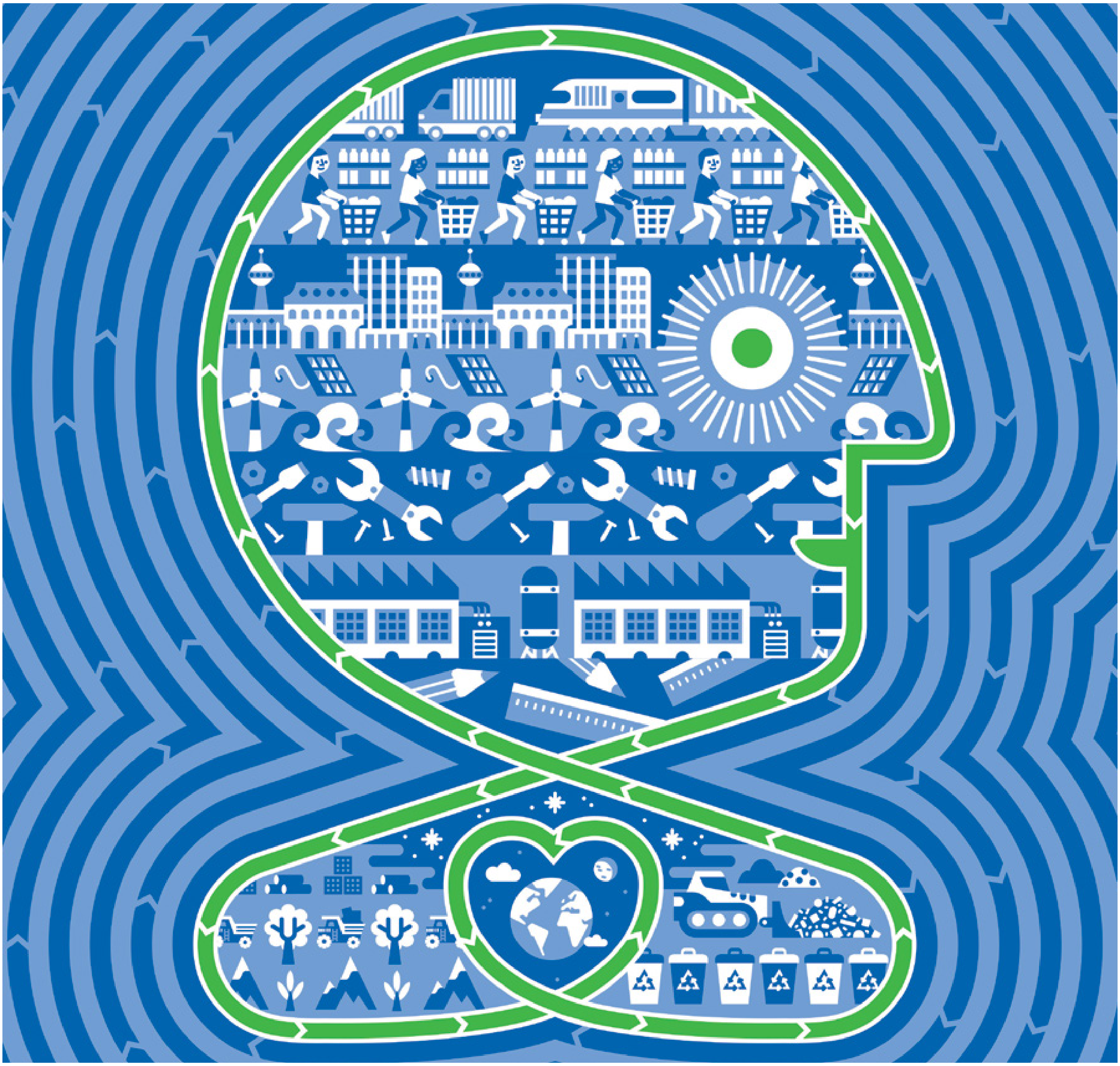

Charting a path towards material sustainability

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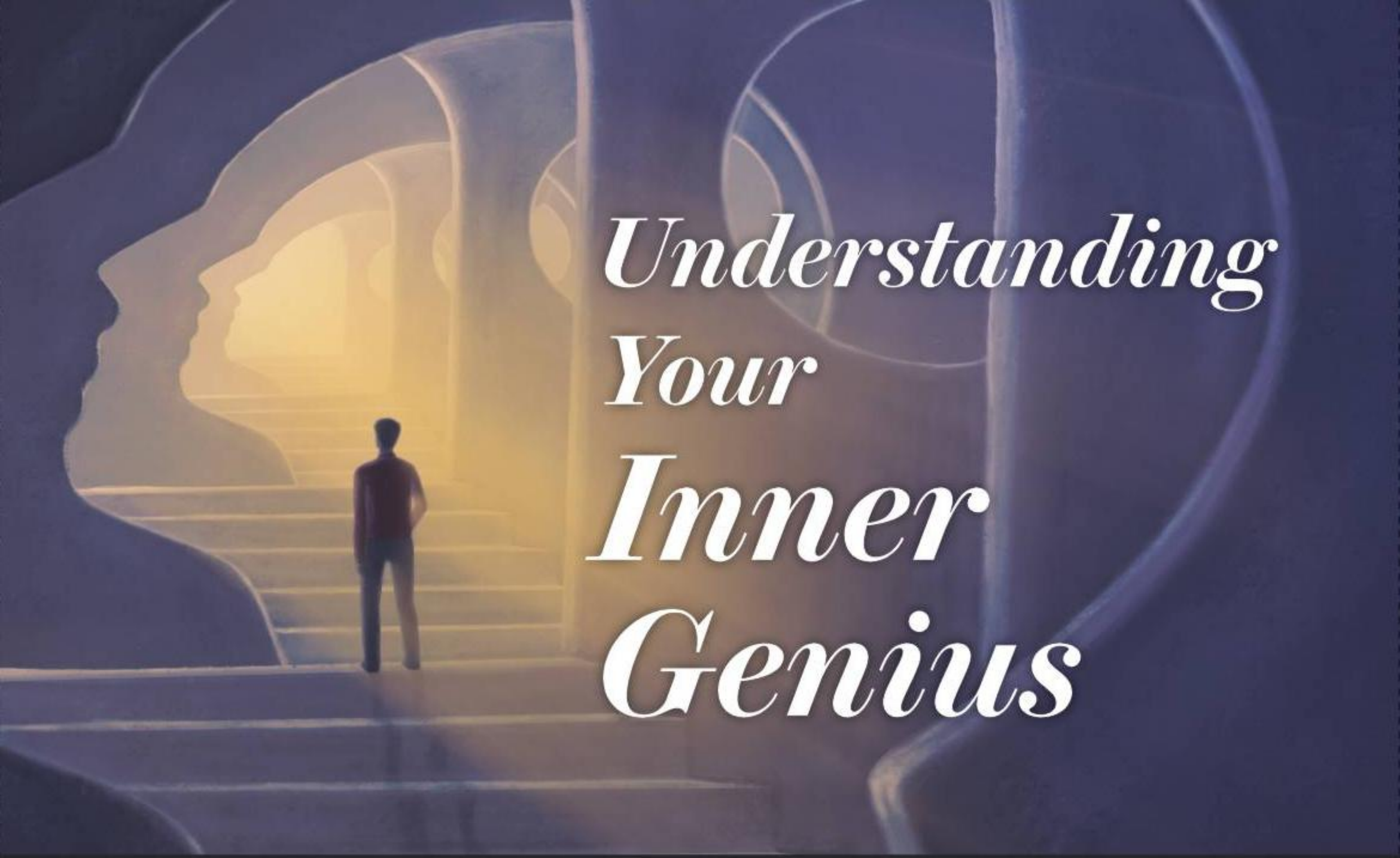

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At a family gathering in August, I gave a brief tribute to my mother on the occasion of her 90th birthday. As the guests sipped their coffee in the warm summer air, I ticked off a dozen or so pieces of wisdom that she has imparted to her family over the decades. One insight that I credited to her was an aversion to waste. In our household, items such as clothes and toys would have multiple lives before being thrown out, and leftover food would be transformed into tomorrow's lunch. In other words, my mother was an early advocate of the circular economy, in which materials and products have multiple iterations, and the waste of one process loops back and becomes the input for another.

For people of her generation, these are commonly held values. But younger generations have largely strayed from these ideas, opting instead to produce and consume more and more. Some of the waste is recycled, but that only goes so far towards addressing the problem that the planet has limited resources to offer.

The finiteness of this supply distinguishes materials from energy. There's little doubt that in the future we will be able to capture more solar power and even build nuclear fusion reactors to abolish energy scarcity forever. But for material resources, no such technology is in view.

That's what makes the research reported in this Outlook so important. As the world sets out to put its economies on a sustainable footing, this Outlook looks at the progress and barriers to the sustainable use and re-use of plastics (see page S2); electronic devices such as mobile phones (S8); building materials (S18); and clothing and other textiles (S20). It also examines the transition of biofuels to a more environmentally friendly form that will foster less soil-depleting and carbon-producing agriculture (S15), and the urgent need to become better stewards of Earth's water resources (S12). Two researchers also debate whether plastic recycling is central to the advancement of the circular economy (S7), or a counterproductive distraction from the need for more fundamental change (S6).

We are pleased to acknowledge the financial support of Google in producing this Outlook. As always, *Nature* retains sole responsibility for all editorial content.

Herb Brody
Chief supplements editor

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On the cover
The circular economy minimizes waste and maximizes reuse.
Credit: Jan Kallwejt

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PLASTIC'S MESSY END-GAME

A circular plastic economy will require a coordinated effort of increased recycling, better product design, a shift towards renewable resources and an end to the production of single-use plastics.

By Sarah DeWeerdt

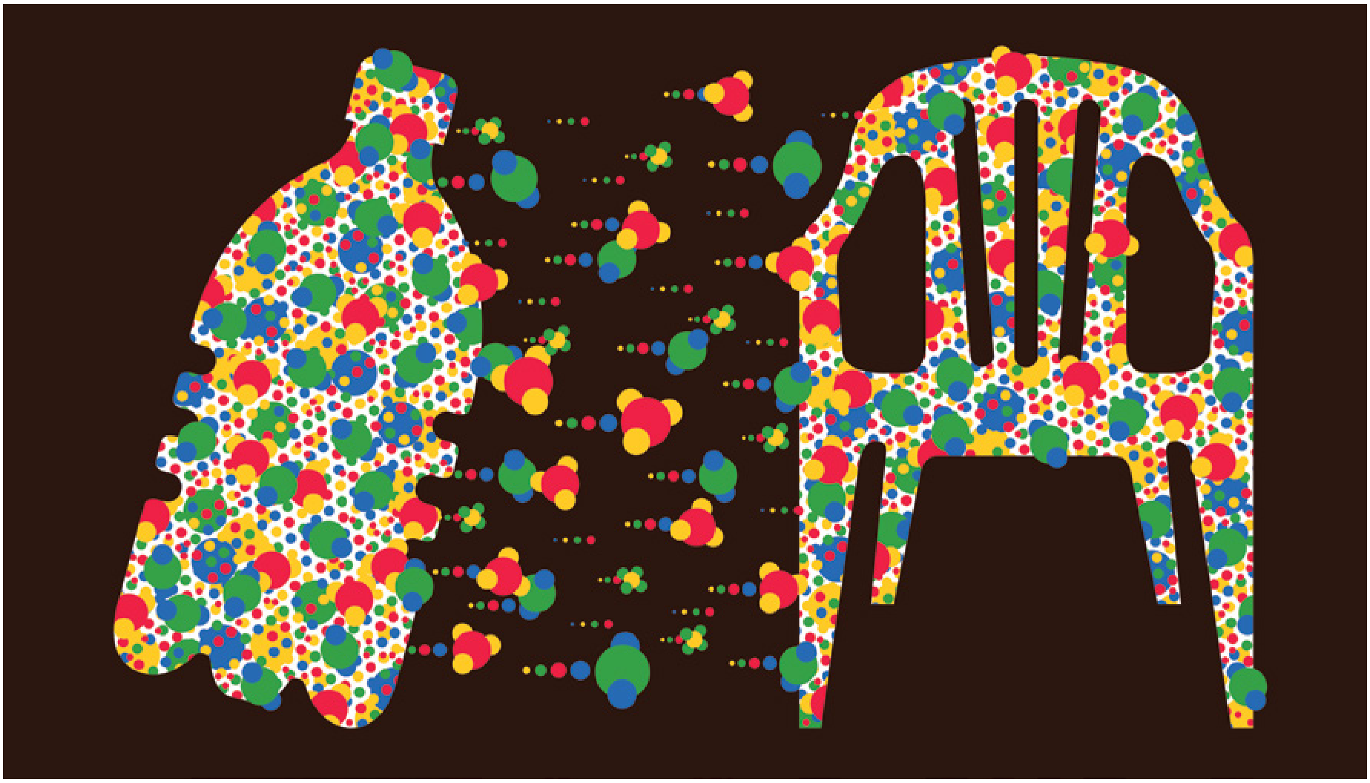


ILLUSTRATION BY JAN KALLWEIT

There's a soap dish for sale at a beauty products shop in São Paulo, Brazil. An off-white disc with a smooth, rounded shape like a river stone, it is just one of millions of plastic soap dishes on offer in shops around the world. But, although most plastics are made from petroleum, some of the plastic in this dish started out as methane generated by a water-treatment facility in California.

Inside a 10-metre-tall bioreactor at the facility, ancient bacteria known as methanotrophs transformed the methane into a molecule called poly(3-hydroxybutyrate), or P3HB. The bacteria use P3HB as a kind of internal battery for energy storage. But a biotechnology company called Mango Materials in Redwood City, California, uses P3HB as a raw material, harvesting granules of it from the bacteria and manufacturing them into lentil-sized pellets called nurdles. These nurdles, the common currency of the plastics industry, then became the soap dish.

Mango Materials is part of a growing effort among scientists, non-governmental organizations and companies large and small to make plastics more sustainable. "We have a long, long way to go," says Molly Morse, a biopolymers engineer and chief executive of Mango Materials. The company produces less than 45 tonnes of P3HB annually, a mere nurdle-sized amount of the estimated 400 million tonnes of plastic produced every year. Plastic can be found in food packaging, building materials, electronics, clothing and a host of other aspects of modern life.

The plastics industry depends on non-renewable resources. More than 90% of global plastic production consists of primary plastics – which are newly manufactured, rather than recycled – made from petroleum products. This reliance requires a huge amount of energy and produces greenhouse-gas emissions. By 2050, emissions from plastic production could amount to 15% of the estimated carbon budget needed to keep global warming below 1.5 °C (ref. 1).

Plastics also create a massive waste management issue. “The sheer volume of waste that’s created is unlike any other supply chain,” says Katherine Locock, a polymer chemist at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Melbourne, Australia.

Roughly 70% of the plastics that have ever been produced have already been discarded[2]. Single-use plastic, especially packaging, makes up around 40% of plastic production in Europe[3]. Yet the most widely used plastics persist in landfill sites or the environment for decades or even centuries after being thrown away.

In theory, many commonly used plastics can be recycled. But only about one-tenth of the plastics that have ever been produced have been recycled once, and only about 1% have been recycled twice[4]. “It is cheaper to just make a new plastic product than to collect it and recycle it or reuse it,” says Kristian Syberg, who studies plastic pollution at Roskilde University in Denmark. “That’s a systemic problem.”

Changing that picture will require action on multiple fronts: scaling up established recycling technologies, rolling them out across the world, developing technologies to deal with hard-to-recycle plastics, leveraging insights from nature to aid both production and disposal of plastics, and reining in the production of single-use plastics. But the results could have benefits for the circular economy more broadly. “There’s a lot we can learn from what’s happening in the plastic space, which is incredibly active, to apply to other sectors,” says Sarah King, a circular economy researcher at Swinburne University of Technology in Melbourne, Australia.

A better sort

Studies show that to make plastics more sustainable, recycling needs to be massively scaled up worldwide. Most of the plastic recycling that occurs today is a type known as mechanical recycling. Plastic waste is collected, cleaned, sorted, shredded and then melted down and formed into pellets to be sold to producers of recycled plastic products.

The process sounds straightforward but it is far from simple in practice. “With plastics, the problem is there’s so many different types,” says Ed Cook, who studies waste plastics as part of the circular economy at the University of Leeds, UK. Different types of plastic don’t mix well when they are melted down and small amounts of the wrong type can degrade the quality of a whole batch, so plastic has to be carefully sorted first.

In high-income countries, this sorting usually happens with the help of high-tech machines at large-scale recycling facilities. These facilities typically target the most commonly used plastic types, especially polyethylene terephthalate (PET, used to make fizzy drink and water bottles), high-density polyethylene (HDPE, found in milk and shampoo bottles), and sometimes low-density polyethylene (LDPE, used for plastic carrier bags) and polypropylene (bottle caps and crisp packets).

Even with diligent sorting, recycled plastic is almost always of lower quality than primary plastic. More than 10,000 different additives can be used to give plastics different colours and technical properties. Plastics of the same type often contain different combinations of additives, resulting in recycled material with unpredictable and often suboptimal additive combinations. Plus, the long polymer chains that make up these materials become slightly shorter each time they are melted down.

> **“THE SHEER VOLUME OF WASTE THAT’S CREATED IS UNLIKE ANY OTHER SUPPLY CHAIN.”**

All these factors mean that plastic recycling usually amounts to downcycling – creating products with less stringent technical or aesthetic qualities. For example, a food-grade plastic beverage bottle becomes a fleece garment, or components for a park bench.

Because manufacturers can’t make many products with recycled plastic, the market for it is limited, says Magdalena Klotz, a graduate student of ecological systems design at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland. Klotz and her collaborators have shown that even if 80% of plastic in Switzerland was collected for recycling, at most only about 20% of it would wind up in recycled plastic products[5]. “It’s not sufficient if we only collect more,” she says. Without other changes to the plastic system, “we get secondary material which cannot be utilized”.

To streamline mechanical recycling and improve the quality of secondary plastics, some researchers are working to develop chemicals called compatibilizers, which help different types of plastic to mix together evenly when they are melted down. “This is an old field, but the idea of applying it to recycling has gained a lot of traction more recently,” says Megan Robertson, a chemical engineer at the University of Houston in Texas. Several compatibilizers that can aid mixing of specific types of plastic are now commercially available, and Robertson is working to develop a more flexible compatibilizer that could be applied to diverse mixes of polymers.

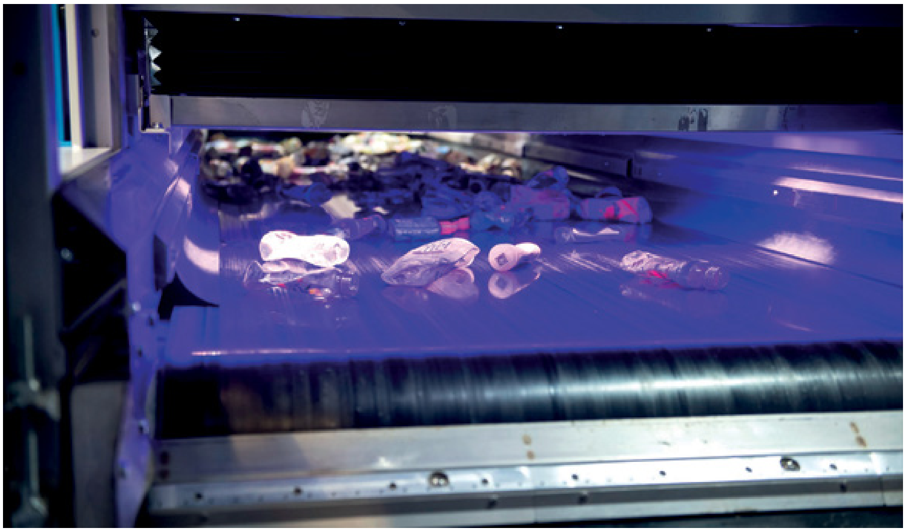
Other efforts aim to improve sorting to ensure a purer, more uniform stream of plastic entering the recycling process. The HolyGrail 2.0 project – a collaboration between more than 160 companies and organizations involved in plastic packaging, facilitated by the European Brands Association and funded in large part by the Alliance to End Plastic Waste – is piloting the use of digital watermarks in Europe. These are codes embedded in plastic packaging that can be read by specialized cameras in recycling facilities and contain information about the attributes of a piece of plastic waste, such as the additives it contains. Another approach is known as aligned design, which calls on plastics manufacturers to coordinate to make products with fewer types of plastic and use the same set of additives. Then recycling facilities would receive a larger volume of similar plastics, in turn yielding higher quality recycled plastics. “An easy win would be to simplify things a little bit more,” Cook says.

Some companies are starting to take these ideas on board. In August, the Coca-Cola Company based in Atlanta, Georgia, began packaging Sprite, its lemon-lime carbonated drink, in clear plastic bottles in North America, rather than the iconic green bottles it has used for 60 years. The goal, the company says, is to aid the recycling of its bottles back into bottles, rather than into other products that are harder to recycle. That, in turn, will help Coca-Cola to meet its own pledge to increase the amount of recycled content in its packaging. The move highlights what researchers say is key to increasing recycling rates: boosting market demand for secondary plastics. “We really could solve this waste problem of plastics if the people making plastics need this waste as a feedstock,” says André Bardow, a chemical engineer at ETH Zurich. “And that makes me hopeful.”

Global improvisation

Plastic is cheap to produce, an accessible and practical material for people living in informal and remote settlements with little access to refrigeration and sanitation. Additionally, its light weight makes it less energy intensive to transport than other food and beverage packaging materials. As a result, these products are found everywhere in the world, even in the remotest places, says Costas Velis, a sustainability scientist at the University of Leeds.

And there’s the catch: because waste plastic has so little value, there’s no economic incentive to collect it from those isolated locations.



Left: A prototype sorting unit tested by the smart-packaging initiative HolyGrail 2.0 could improve the separation of plastic waste.

L TO R: DIGITAL WATERMARKS INITIATIVE HOLYGRAIL 2.0; JUNI KRISWANTO/GETTY; TSVIBRAV/GETTY

Indeed, plastic waste is pervasive through many low- and middle-income countries, where formal recycling programmes are rare. In fact, an estimated two billion people worldwide lack access to regular waste-management services[6]. Most of the estimated 13 million tonnes of plastic that enters the oceans annually comes from areas with inadequate waste management.

Nevertheless, a surprising amount of plastic recycling happens in low- and middle-income countries. In these places, recycling tends to be part of the informal economy. Waste pickers sift through landfill sites and bins and collect plastic from the environment. Research by a team including Velis and Cook has shown that these people's efforts add up: "The waste pickers are behind more plastics recycling globally than the formal industry," Velis says.

These informal workers are often entrepreneurial and adaptable. In Ghana, waste collectors have begun going door-to-door purchasing some of the most desirable plastics such as HDPE for recycling, says Kwaku Oduro-Appiah, a waste-management scientist at the University of Cape Coast in Ghana. In turn, Oduro-Appiah says, "some householders are now seeing some value and would not want to add [plastic] directly to the waste". Other waste collectors go to events such as weddings and collect the disposable plastics used there, realizing that the cleaner plastic will fetch a higher price than items that have been picked out of a landfill, he says.

However, waste pickers and collectors in Ghana and other low- and middle-income countries tend to be living in poverty, often come from marginalized communities and their waste-collection activities are sometimes criminalized. Their work can be hazardous, especially in landfill sites, and "they don't get even value for money because they don't have the power to bargain", Oduro-Appiah says. But that's beginning to change. Recognition of the waste pickers' contributions and concern for their working conditions is prompting efforts to include them in waste-management planning, such as in Ghana's National Action Roadmap for plastic waste that launched in 2021.

> "WASTE PICKERS ARE BEHIND MORE PLASTICS RECYCLING THAN THE FORMAL INDUSTRY."

Some of the plastic collected by waste pickers ends up at recycling plants in larger countries such as Brazil and Indonesia, which have local plastics industries. Some is shipped abroad for recycling. Some is recycled locally by small-scale businesses, with workers turning to YouTube videos to learn and share skills. "These are very small-scale operations without any environmental and public-health protection," Velis says. Still, "there's a lot of improvisation across the global south", he adds.

Advanced breakdown

Although efforts continue to boost established recycling approaches around the world, the past decade has also seen increasing research attention turn to advanced recycling technologies, sometimes called chemical recycling. These methods have not yet been employed widely on a commercial scale, but they could eventually allow recycling of plastic types and products that can't be mechanically recycled.

One such method is pyrolysis, a procedure in which plastics are heated to high temperatures in the absence of oxygen. This causes the polymer chains to break down into smaller components. Pyrolysis can be used for mixed plastic waste – potentially enabling the recycling of various products composed of multiple layers of different plastics.

So far, most research on pyrolysis has focused on turning plastic into fuel – an energy-intensive process that results in the carbon contained in the plastic being emitted into the atmosphere. But in theory, the smaller molecules that pyrolysis yields could be reassembled back into plastics.

Another advanced recycling approach is to break down plastic molecules into their individual subunits. These could then be reassembled into polymers, circumventing the shortening chains and degradation of quality that happens with mechanical recycling. This could aid the recycling of thermosets – a class of polymers that cannot be melted down, and therefore cannot be mechanically recycled. These polymers are used to produce materials such as bakelite, melamine and the epoxy resins used in wind-turbine blades.

Chemical recycling also opens up the possibility of upcycling: making chemical products from the monomers that are more valuable than plastics, and difficult to produce by other means. "Usually these are not large scale chemicals," Bardow says, but some still have key roles in certain industries, such as 3-hydroxy-γ-butyrolactone, which is used to produce cholesterol-lowering statin drugs. The high value of these compounds could provide a financial push to develop chemical

Centre: A worker sorts plastic bottles in Surabaya, Indonesia. Right: Birds can be easily trapped in discarded plastic netting.

recycling technology, Bardow says.

A huge barrier to chemical recycling is that plastic polymers are very stable – which is what makes plastics so useful in such a wide variety of applications – so it takes a lot of energy to break them apart. Researchers are looking for enzymes and catalysts that could reduce the energy required. "That's really where the game is right now for chemical recycling," Robertson says.

Natural inspiration

To look for the enzymes and catalysts that could aid chemical recycling, "we can go to places where they're already present in nature", says Craig Criddle, who specializes in microbial biotechnology at Stanford University in California. (Criddle was a PhD co-adviser to Morse; some of the approaches Mango Materials uses came out of work from his laboratory.) Polymers of various sorts are common in the biological world, and sometimes organisms' solutions for breaking down natural polymers can be harnessed to disassemble human-created ones, he says. Criddle's research focuses on mealworms (*Tenebrio molitor*), which he dubs "tiny little bioreactors". These invertebrates can digest multiple plastics with the help of their gut microbial community. Other researchers have identified bacteria that can break down multiple types of plastic into the same end product, more evidence that specific microbes – or molecules derived from them – could help with recycling mixed plastic-waste streams.

Researchers are looking to the natural world to make other aspects of the plastics industry more sustainable and circular as well. There has been a surge of interest in plastics produced from renewable feedstocks such as sugar and corn rather than fossil fuels. However, these bioplastics still only account for a small fraction of plastics produced today, and if that were to scale up significantly it could create pressure on agricultural lands and water supplies. These concerns inspired Mango Materials to produce its P3HB from methane, a potent greenhouse gas that is a product of wastewater treatment plants, landfill sites and agricultural facilities. Methane is cheaper than other renewable feedstocks – and plastic is a more valuable material than other products that can be made from methane, Morse explains.

But there are downsides to bioplastics. "They're typically different polymers" than those made from fossil fuels, Syberg says. "So they don't fit very well into the recycling systems that we have at the moment." Take P3HB: the technology exists to recycle it, but the facilities do not, because so little of it is currently produced. (P3HB is also biodegradable in home compost piles, providing another disposal solution.)

Beyond recycling

By 2050, global plastic demand is projected to nearly triple to 1,100 million tonnes per year[1]. In an analysis released earlier this year[7], Bardow and his team found that scaling up recycling, relying more on renewable feedstocks and implementing other strategies to make the plastic industry more circular could keep the current level of plastic production within "planetary boundaries". But if plastic production continues to grow at the predicted pace, then options greatly diminish – and by 2050, Bardow says, there will be no sustainable solution "even with all the tricks that chemists and chemical engineers can pull".

The findings highlight the need to reduce overall use of plastic, especially single-use items. "If we just turn from making oil-based single-use plastic products to renewable-based single-use plastic products, then we haven't gotten very far," says Syberg (see page S6).

So far, research that could support this transition is scarce. Syberg and his team analysed plastic research relevant to Europe, and found that most studies focus on recycling and the waste phase of plastics, with little attention to other parts of product life cycles[8]. Similarly, King and Locock conducted a comprehensive review of circular-plastic-economy research worldwide, and found that more than one-quarter of studies focused on recycling, but less than 10% on topics such as repair and reuse[9].

Efforts to improve plastic circularity continue. Mango Materials is seeking a location for a facility that could produce up to 2,300 tonnes of P3HB per year – an order of magnitude leap in capability, although still just a tiny fraction of overall global plastics production. "It's fun to try and be part of the solution," Morse says. "But it's also very daunting."

Sarah DeWeerdt is a science writer based in Seattle, Washington.

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Path to sustainability

Recycling can only get us so far, says Kristian Syberg. The real solution to transforming the plastic economy lies in making less in the first place.

Plastic pollution is recognized as being one of the major global environmental challenges today, with a worldwide reach that is affecting essential Earth systems such as the climate and biodiversity. As a result, in March the United Nations Environment Programme declared its intention to develop a treaty by 2024 to "end plastic pollution". However, although the declaration lays out overall aims for reducing plastic pollution, it does not mention any specific policy measures (see go.nature.com/3rgujfc). An efficient and ambitious treaty has the potential to facilitate the much-needed transition to a circular plastic economy, and mark the beginning of a reduction in the rate of plastic pollution. But to achieve this, it is paramount that the new treaty does not become a doctrine for recycling at the expense of providing a legal foundation for reducing plastic consumption.

For many years, the transition to a circular plastic economy has been understood to require a combination of efforts, often summarized by the mantra 'reduce, reuse, recycle'. The principles are based on the top three levels of the waste hierarchy, whereby reducing is better than reusing, which is, in turn, more favourable than recycling. In practice, however, attention has primarily been focused on recycling, owing to an assumption that a massive improvement in recycling rates will be crucial for the circular transition.

Adjust the focus

A document published by the European Commission in 2018, outlining how the plastic economy should be transformed, serves as a good example of this tendency (see go.nature.com/3clrqdq). The word 'recycle' and its derivatives appear 144 times, whereas words rooted in 'reuse' and 'reduce' occur only 12 and 18 times (and most mentions of the latter relate to reducing environmental litter, not plastic consumption). Of the nine specific targets listed as part of the European Union's 'vision' for a new plastics economy, seven relate exclusively to recycling.

The focus on recycling had two implications. First, it is likely to result in member states implementing measures to increase recycling – and therefore not actively working towards any reduction targets. Second, it could actually deter states from setting reduction targets because such targets could make it harder to meet recycling demands, owing to an overlap between the plastic that could easily be collected for recycling and that which could be reduced.

EMIL ASMUSSEN

"It is unrealistic to expect a near-perfect system to be achieved in the near future."

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The idea of recycling being the optimal solution is built on the thinking that a near-perfect closed-loop system can be achieved, and that if materials are kept in the circular value chain we can use them indefinitely. This is unfortunately far from the truth. According to the Organisation for Economic Co-operation and Development, only 15% of plastic waste is collected for recycling, and, of that, 40% is discarded from the recycling process on account of its low quality. As a result, actual plastic recycling rates are as low as 9%.

Moreover, most plastic sent for recycling, especially that collected from households, is downcycled – that is, the recycled product is of a lower quality than the original – on account of its heterogeneous nature. To avoid any loss in quality during the recycling process, waste fractions must be kept uniform, with fractions typically consisting of single polymers without additives such as pigments. New and better recycling technologies will improve this, but it is unrealistic to expect a near-perfect system to be achieved in the near future.

Don't create dependence

Massive investments in recycling infrastructure could lead to a 'lock-in' situation, whereby we build a sector with infrastructure that makes us dependent on the recycling of most plastics – even if that is not the optimal solution. Such a scenario has resulted in some countries making major investments in incineration plants that facilitate the continuous burning of waste to produce energy. In Denmark, where massive past investments were made in such plants, waste now needs to be imported to ensure that these incinerators meet their energy production targets.

It is therefore essential that the UN plastic treaty aims to not merely increase recycling rates, but also to reduce the consumption of both plastic and the other resources that plastic enables us to consume. It should be noted that there is also a need for the treaty to develop waste-handling systems in parts of the world where this is currently poorly managed, but that is not, in itself, a long-term remedy. The solution to ending plastic pollution – the resolution's aim – lies in providing incentives to a transition that builds on reducing non-essential plastics use and making products that last for as long as possible.

Policymaking will be at the centre of this transition, and inspiration can be found in both prior experiences and current processes. Ireland, for example, was one of the first countries in Europe to put a levy on plastic bags. This policy resulted in a 90% drop in consumption and the generation of more than US$9 million for a green public fund. Meanwhile, the trend in EU policy is shifting slightly towards promoting better design and longer-lasting products. The new EU Ecodesign Directive, for example, will outline specific measures that could serve as an inspiration for how policies can promote sustainable production.

Such efforts are important steps in the transition to a circular plastic economy – and should guide the writers of the UN plastic treaty in their efforts. In the end, that treaty will become a key component in the circular transition of the plastic economy only if it guides policymakers to put in place far-sighted measures that make it worthwhile for manufacturers to make long-lasting products. That is the key to a sustainable plastic future.

Don't discount recycling

Although often dismissed as insufficient, the process remains key to quickly bringing about a circular economy, says Sarah King.

COURTESY OF SARAH KING

Evidence of the economic opportunities that a circular economy could bring is mounting. The potential environmental impact is also clear. The move to a circular economy – a system that aims to reduce, reuse and recycle materials – could address 70% of global greenhouse emissions[1]. As the benefits stack up, this transition is becoming a key focus for policymakers around the world. But there remains much confusion about what a circular economy is, and how it might be achieved.

One common misunderstanding is the notion that it is simply a rebrand of recycling – the recovery and reprocessing of waste materials for use in new products. This perception is reinforced because recycling is the most common component of almost 80% of circular economy definitions[2]. But, although recycling is an important element, there are many others. Before recycling comes into play there are several steps in a product's life cycle that should be addressed, such as redesigning products and processes so that they use less virgin material, and re-using items rather than discarding them. New business models such as sharing and repairing can be adopted[3]. These approaches prioritize smart designs that extend a product's useful life, before reaching the stage of recycling. These steps are consistent with the central aim of a circular economy: to provide economic productivity by eliminating the concept of waste.

Recycling is often criticized as insufficient compared with earlier interventions such as reuse or reduce. And it is true that a circular economy requires a great deal more than recycling. But recycling remains a fundamental strategy to extract value from resources, as evidenced by its current contribution to 8.6% global circularity[1].

> "Recycling remains a fundamental strategy to extract value from resources."

To improve recycling rates, we need to recognize that the waste and resource recovery sector is positioned at the end of the supply chain, often known as end of life. This sector has limited influence over the materials and resources they collect. Recycling could improve if more effective changes are made upstream, such as in product design, material use, manufacturing, collection infrastructure and consumer behaviours.

Many countries, institutions and organizations need to increase resource recovery and shift away from the cheapest waste-management solutions such as landfill and incineration. This is a key barrier to realizing a circular economy. In Australia, there was significant disruption to recycling pathways in 2018 when, similarly to other high-income nations, the country could no longer export waste (including plastic and paper recycling) to China. This resulted in recycling being directed to landfill for a short period. For plastics alone, Australia required a 150% increase in domestic plastics-recycling capacity and this highlighted a need to adopt a range of circular economy strategies.

The transition to a circular economy will need further cross-sector collaboration and investment in initiatives that improve recovery rates while minimizing the consumption of raw materials, extending product life and increasing the use of renewable resources. An example is so-called right to repair legislation, which requires manufacturers to modify product design and make parts available to allow consumers to mend products. The right to repair is being adopted in Europe for electronic goods but could be applied to other products. Another example is the United Kingdom's £200 (US$226) per tonne tax on plastic packaging that doesn't include at least 30% recycled plastic. This approach is driving up market demand for recycled content and encourages companies to adopt recycled plastic solutions.

The Australian government has also implemented a waste export ban for key materials – including tyres, plastics, glass, paper and cardboard – and announced an investment of AU$1 billion (roughly US$620 million) into infrastructure to enhance the country's ability to recover and remanufacture waste materials. Product stewardship schemes, whether government mandated or voluntary, would require manufacturers and consumers to be responsible for a product throughout its life cycle, including its end-of-life stage. This initiative encourages companies to ensure their products can be recycled, such as by improving their design, or by implementing collection and recycling solutions if none already exists.

Ultimately, we need to break traditional boundaries between brand owners, manufacturers and those in the business of waste management and resource recovery, and instead stimulate collaborative partnerships. For example, nine companies joined forces to create a circular supply chain in which they captured soft plastic waste and converted it to a Nestlé KitKat wrapper using Australian-designed advanced recycling technology. This process converts waste plastic to food-grade plastic, in a continuous loop.

Innovation – on both the technological and societal fronts – is essential in the transition to a circular economy. Such shifts are needed to eliminate the concept of waste, by reducing consumption, and an increase in reuse and recycling. Local and global collaborations between government, industry, not-for-profit organizations and research agencies will help to address particularly nasty waste problems, such as plastics in the ocean.

It's certainly true that a circular economy is much more than just recycling. But increased focus on this essential process is an effective strategy to achieve the larger goal.

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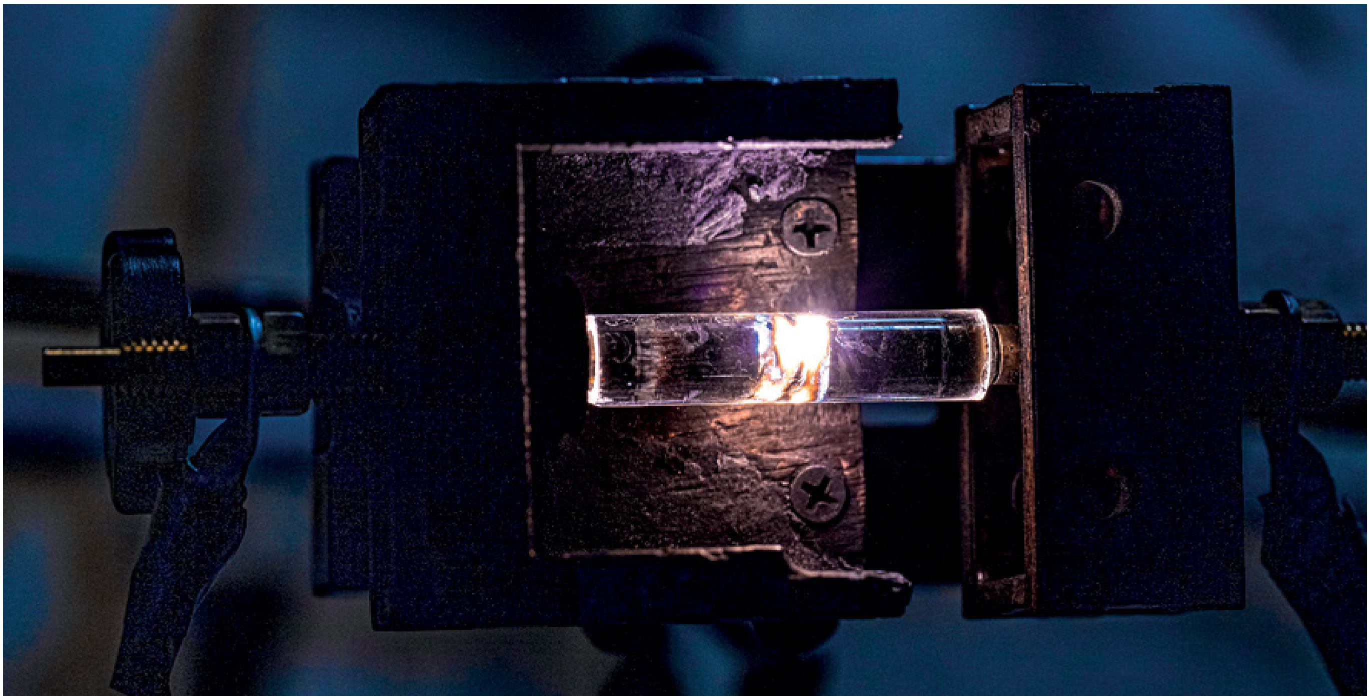
Upgrading the electronics ecosystem

There are no quick or easy fixes for the continuing global electronic-waste crisis, but a combination of technological and policy solutions could help to limit the damage. **By Michael Eisenstein**


JEFF FITLOW, RICE UNIV.

Flash Joule heating is a process that extracts valuable rare-earth elements from electronic waste.

Your smartphone begins life neatly packed into a well-designed box. Chances are it will end its days in a more ignominious manner.

Assuming it doesn't end up rattling around in a junk drawer, it will most likely go to the same landfill as your other household waste, where it will slowly leach toxic chemicals into the soil and water. Or worse, it might be shipped to another country, where low-income workers will manually break the phone apart to recover anything of value and burn or bury the rest, putting their health – and that of their wider community – at risk in the process. Meanwhile, miners continue to plunder Earth for metals and minerals to feed our unquenchable hunger for new gadgets.

The problem posed by electronic waste, or e-waste, is only getting larger. "It's the fastest growing waste stream," says Pablo Dias, an engineer specializing in management of e-waste at the University of New South Wales in Sydney, Australia. According to the Global E-waste Monitor, a project backed by the United Nations Institute for Training and Research, people disposed of 53.6 million metric tonnes of e-waste in 2019 – a quantity that is expected to increase by nearly 40% by 2030 (ref. 1).

Oladele Ogunseitan, a public-health researcher at the University of California, Irvine, thinks things are starting to change. "We are making enough noise that the manufacturers are not able to ignore it anymore," he says. And there are ample opportunities to circularize the electronics industry. The precious and scarce metals these devices contain can be reused near-indefinitely, and emerging technologies that make their recovery easier could drastically reduce the need for mining. Parallel progress in recyclable and biodegradable circuit boards could eliminate the more toxic ingredients in electronics and allow consumers to bin defunct devices without guilt.

"This is an opportunity to stop thinking of it as waste," says Clara Santato, a chemist specializing in electroactive materials at Polytechnique Montréal in Canada. But making electronics more sustainable will also require a more radical evolution of the industry as a whole, as well as the consumers who crave their products.

Swept under the carpet

E-waste is a category that comprises a diverse array of electrical equipment, for which the material can vary as much as their form and function. One estimate suggests that as many as 69 different chemical elements might be found in e-waste[1]. "We looked at 10 different smartphone printed circuit boards, and found that the variation in material content was quite significant," says Jeff Kettle, an electronics engineer at the University of Glasgow, UK.

Standard building blocks such as silicon, iron and copper are typically joined by more exotic elements. These include highly conductive precious metals such as platinum and gold, as well as rare-earth elements such as neodymium, which possess unique magnetic and electrical properties. Although not geologically rare, these elements are logistically difficult to obtain and mainly sourced from just a few countries – most notably, China. Some devices also contain heavy metals such as lead and cadmium that seriously threaten human and environmental health.

E-waste contains these hard-to-find elements in abundance. If the useful materials can be efficiently separated from those that are not, then waste could become a gold mine, both literally and figuratively. "When you find rare-earths in ores, they come in parts per million – when you have them in magnets, they come in percentages," says Ikenna Nlebedim, a materials scientist at the Ames National Laboratory in Iowa. The quality of these recovered elements is also assured: they have already been deemed suitable for use in electronics. Similarly, estimates suggest that precious metals might be up to 50 times more abundant in e-waste than in mined ores.

The Global E-waste Monitor reports that, as of 2019, only around 17% of the world's e-waste was being properly managed for recycling in the countries that generate it[1] (see 'The digital dumping ground'). The rest is nearly impossible to account for and presumably ends up in local landfills, wasting valuable materials and inflicting lasting environmental damage. But a sizable fraction of this material is offloaded onto countries in Asia, Africa and Latin America. Robust numbers are hard to come by, but a 2016 monitoring study by the Basel Action Network, an environmental watchdog in Seattle, Washington, found that up to 40% of e-waste thought to be slated for recycling from the United States might be exported[2].

Ogunseitan sees several reasons why recycling hasn't taken off in the United States. "Economically, it's difficult to make a big profit, but also we have a lot of environmental laws that keep out factories that would easily dismantle and smelt," he says. Many regions also lack effective collection systems for recovering household and business e-waste. And so this waste ends up in Ghana, Vietnam, Brazil and other countries, where networks of informal recyclers manually strip shiploads of discarded electronics. E-waste export is heavily restricted by the Basel Convention, a United Nations treaty that took effect in 1992. But the United States has never ratified the convention. There are also significant loopholes – for example, some exporters misrepresent e-waste as donations.

Informal recycling has become an important, albeit dangerous, source of livelihood for some people in these countries. "People manually take out the things that are more valuable, such as printed circuit boards, hard drives and memory, and send these back to the high-income countries for further processing," says Dias. The remainder is burned or just piled on the ground, creating a continuing public-health catastrophe. A 2012 study revealed that inhabitants of a rural e-waste processing community in China were 60% more likely to develop lung cancer than were people living in the nearby major city of Guangzhou[3]. This was due to inhalation of toxic-waste by-products, which are released into the air after incinerating e-waste.

Several countries have successfully pushed for change – between 2018 and 2021 China moved to reject all imported solid waste after decades of damage. But this ultimately results in the waste being directed elsewhere, and the scope of the problem remains daunting.

Ripe for recovery

A practice known as urban mining offers one solution for improving the management of e-waste and incentivizing countries to retain and process their leftovers rather than burying, burning or exporting them. This involves chemical or physical processes to separate precious metals or rare-earth elements present in e-waste from materials that are toxic or of little value.

Two approaches currently predominate in urban mining. Pyrometallurgy, in which preprocessed waste material is heated to extremely high temperatures – often upwards of 1,000 °C – to burn away plastics and other unwanted materials and yield a mixed fraction of molten precious metals that can then be purified. "The downside is that these approaches are energy intensive," says Nlebedim. As an alternative, some facilities use strong acids to dissolve the metals present in e-waste. Although less energy intensive, Nlebedim notes that this hydrometallurgic method has its own negative environmental footprint, producing acid-laden toxic sludge and lots of waste water.

> **"We are making enough noise that the manufacturers are not able to ignore it anymore."**

Urban-mining operations are currently active at a relatively small number of facilities worldwide. But the profit margins can be slim, which has limited the growth of this sector. "They require very big volumes to be able to be profitable, so it's hard for another small player to come in and compete with them," Dias says. The costs associated with urban mining – such as preprocessing, metal purification and waste management – add up quickly, potentially shifting the cost equation back in favour of traditional mining. "You can't tell somebody, 'Mine is recycled, pay $10 more per kilogram to buy it,'" Nlebedim says. Fortunately, methods now in development – including a few that are on the verge of commercialization – could tip the balance in favour of recycling.

For example, James Tour, a synthetic chemist at Rice University in Houston, Texas, has applied a technique known as flash Joule heating to rapid, low-cost e-waste processing. Flash Joule heating subjects materials to an intense blast of energy, bringing them to temperatures that vapourize the metals so that only carbon is left behind in the chamber. But unlike pyrometallurgy, the heating is incredibly brief – typically a few hundred milliseconds. The resulting metal vapours can then be extracted under vacuum and condensed by cooling. Flash Joule heating has a clear economic appeal: it can be performed at a cost of roughly US$12 per tonne of waste, with minimal energy and water use required.

In an initial demonstration, this method recovered more than 80% of the precious metals, such as palladium and silver, that were present in an e-waste sample[4], while also enabling easy isolation of toxic compounds such as mercury and lead. "The remainder is clean enough for agricultural soil, even by California standards," says Tour. He and his colleagues are now trying to license the technology to companies for use in urban mining of e-waste.

Nlebedim and colleagues have developed an alternative, acid-free approach to hydrometallurgy for recovering rare-earth elements in the permanent magnets that are commonly found in hard drives and motors[5]. The researchers identified reaction conditions in which the valuable magnetic components are selectively dissolved at neutral pH while leaving other materials intact, which means that minimal processing is required before recycling. The dissolved rare-earth elements can subsequently be purified from the solution, yielding material of sufficient quality for reuse in electronics. This technology is being commercialized by a manufacturing company called TdVib based in Boone, Iowa, which is on track to have its first pilot plant fully operational by the end of 2022. "We are currently running batches of 800 kilograms at a time and will be scaling up in the next few months to batches of about 8,000 kilograms," TdVib chief executive Daniel Bina said in late September.

Waste not

Not everything can be readily recycled, but there are opportunities to create 'green electronics' that can be produced and disposed of in a more environmentally friendly way. Rodrigo Martins, a materials scientist at the New University of Lisbon, is confident that many of the functions performed by modern silicon-based devices could one day be replicated with Earth-friendly alternatives, eventually eliminating the need for scarce metals, non-biodegradable plastics or energy-intensive manufacturing.

Conventional circuit boards are built on fibreglass, which is non-biodegradable and typically laced with potentially toxic fire-retardant compounds. Martins' group is working on paper-based boards that could offer an environmentally friendlier alternative. In 2011, Martins and his collaborator and wife, Elvira Fortunato, described a paper-based complementary metal-oxide semiconductor (CMOS) device[6] – a core component in modern integrated circuits. The conductive materials in this device were based on zinc oxide rather than on silicon, which is typically used, and the use of this substance or other metal oxides could greatly reduce the cost and greenhouse-gas footprint associated with manufacturing.

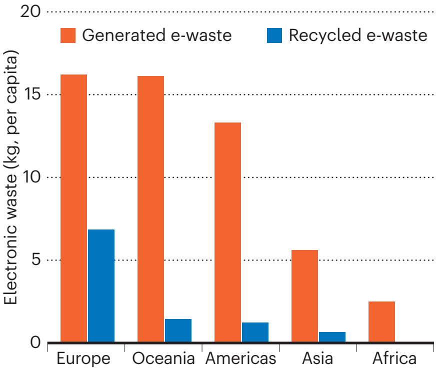
Martins's team has continued to develop techniques for efficient and reproducible printing of paper-based devices, and is exploring the use of alternative materials – including combinations of graphene with common metals such as bismuth and molybdenum. He notes that as their performance improves, the devices get smaller, which confers an additional edge. "It means the amount of raw material that I'm consuming is, by far, less," says Martins. "And I can use materials which are abundant and nontoxic."

Other groups are exploring a variety of alternative biodegradable circuit-board components. For example, Ogunseitan and his long-time collaborator Johnny Lincoln who founded Axiom Materials, a composite-materials manufacturer in Santa Ana, California, are investigating the commercial viability of circuit boards based on flax and a linseed-oil-derived epoxy, which they first demonstrated in 2008 (ref. 7). And Santato's team is looking at the possibility of replacing silicon-based semiconductors with melanin, a naturally derived pigment that is capable of efficient electron transport. This year, Santato's group has demonstrated that melanin-based films can almost match the performance of more-established organic semiconductors[8]. And although their current source of melanin is cuttlefish ink, Santato points out that she could obtain the substance from food waste.

This July saw the formal launch of the UK Green Energy-Optimised Printed Transient Integrated Circuits (GEOPIC) initiative, a programme led by Ravinder Dahiya at the University of Glasgow, for which Kettle is also an investigator, that brings together academic, government and industry specialists to make circuit-board production more sustainable.

THE DIGITAL DUMPING GROUND

In 2019, there were clear regional differences in global electronic waste output, but one pattern is consistent: most e-waste was not disposed of properly.



SOURCE: THE GLOBAL E-WASTE STATISTICS PARTNERSHIP

"GEOPIC is about developing biodegradable integrated circuits, biodegradable substrates, biodegradable interconnects and so on," says Kettle. This will not tackle every aspect of the sustainability problem, but could lead to greener manufacturing processes and far less e-waste in the long term.

How broadly these biodegradable components might overturn the circuit board status quo in the near term remains an open question. "You do have to compromise on performance," says Kettle. Flexible and compostable substrates such as flax or paper are inherently more susceptible to damage from moisture or heat, and devices that use them must be designed with this limitation in mind. Santato thinks that materials scientists are a long way from finding eco-friendly replacements for many scarce metals. "At the moment," she says, "you cannot reach the conductivity of gold or platinum or palladium with organic or carbon-based conductors."

However, recyclable or compostable electronics could become invaluable in devices intended for short-term use, or in narrow-purpose devices such as wearables or environmental sensors that don't have to meet the same rigorous performance standards as the processors found in smartphones. From Martins's perspective, such electronics could be useful in contexts such as monitoring water quality or food safety, or the manufacture of low-cost displays, without meaningfully adding to the planet's e-waste burden.

Creating a culture shift

Many researchers working on the e-waste problem have been pleasantly surprised to find enthusiastic partners in the commercial sector. For example, Ogunseitan is conducting research funded by Microsoft, and Tour says he is in regular contact with companies looking to minimize the impact associated with keeping their IT infrastructure current. "Server farms are changing over every three years, and you get mountains of printed circuit boards," Tour says. These facilities "don't know what to do with all of this toxic waste", he explains.

But more-aggressive measures will probably be necessary, including tighter regulations. Dias thinks that strict bans on landfill deposition of e-waste is a crucial first step. "The biggest competitor for recycling is landfill," he says. With this option off the table, the competition will shift to delivering the most cost-effective recycling service. Dias further emphasizes that this step must also be coupled with more-stringent monitoring and enforcement of export restrictions to prevent a massive surge of e-waste from high-income nations onto the shores of lower-income countries.

Manufacturers should also pursue practices that promote circularity. "There needs to be a very clear policy for 'end of life', where the producer takes back the product," says Santato. A few device manufacturers are already doing this; for example, Amsterdam-based smartphone manufacturer Fairphone reported having recycled as many phones in 2021 as they have sold to consumers. Modular electronic devices designed for easy disassembly and repair could also incentivize recycling by making it easier and cheaper to break down – or service – broken or obsolete devices.

But consumers will also need to play their part – particularly in high-income countries, where it is more routine to replace high-end electronic devices such as smartphones every few years. "We often think of recycling as this silver bullet – it's not," says Dias. "Reducing should be the overarching goal." Planned obsolescence by manufacturers is part of the problem, but resolving this issue will also be a matter of public education and policies that boost civic-mindedness and environmental consciousness. "We can have an amazing device that lasts four or five years and still have a good life," says Dias. "We're not going to have to give up as much as we think we will."

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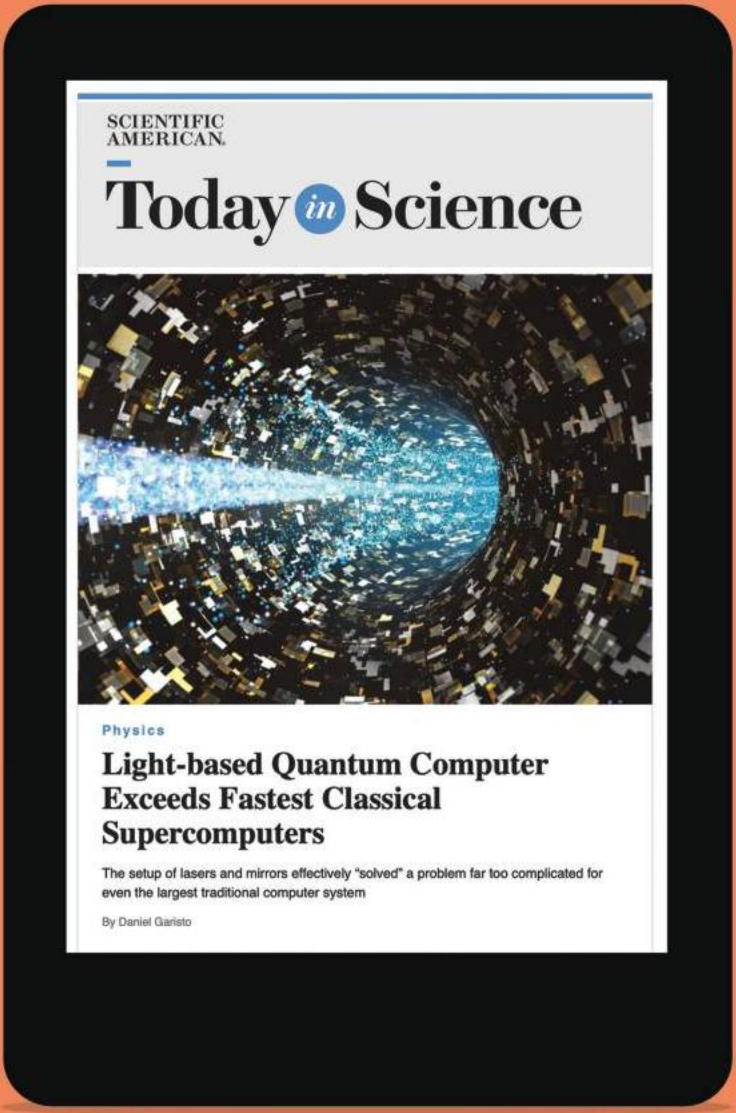

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Today *in* Science

Physics

Light-based Quantum Computer Exceeds Fastest Classical Supercomputers

The setup of lasers and mirrors effectively "solved" a problem far too complicated for even the largest traditional computer system

By Daniel Garisto

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ERICA GIES

Peru's water utility companies are protecting peat bogs because of their ability to hold water.

Smarter ways with water

To address an onslaught of crises, people must tune into natural ways to repair water cycles that human development has severely disrupted. **By Erica Gies**

In just a few months this year, abnormally low water levels in rivers led China to shut down factories and to floods in one-third of Pakistan, killing around 1,500 people and grinding the country to a halt. A dried-up Rhine River threatened to tip Germany's economy into recession, because cargo ships could not carry standard loads. And the Las Vegas strip turned into a river and flooded casinos, chasing customers away. It seems that such water disasters pepper the news daily now.

Many businesses have long lobbied against changing their practices to safeguard the environment, by refusing to implement pollution controls, take climate action or reduce resource use. The costs are too high and would harm economic growth, they argue. Now we are seeing the price of that inaction.

With mounting climate-fuelled weather disasters, social inequality, species extinctions and resource scarcity, some corporations have adopted sustainability programmes. One term in this realm is 'circular economy', in which practitioners aim to increase the efficiency and reuse of resources, including water – ideally making more goods (and more money) in the process.

But the term has its roots in decades of alternative economic theories – known variously as environmental economics, ecological economics, doughnut economics and steady-state economics. These frameworks recognize that the mainstream economics' goal of eternal growth is impossible on a planet with finite resources.

These ideas are beginning to filter into the mainstream, a mark of both the persuasiveness of advocates' arguments and the declining state of the natural world. But the economists and scientists behind these principles say that some businesses and governments are engaging in greenwashing – claiming their actions to protect the environment are more significant than they really are – rather than making the kinds of fundamental change required to move the global economy onto a truly sustainable path.

Because the dominant culture prioritizes human demands, water is generally viewed as either a commodity or a threat. That perspective inspires single-focus problem solving that ignores the complexity and interconnectedness of water's relationships with rocks and soil, microbes, plants and animals, including humans, inevitably resulting in unintended consequences.

Pumping out groundwater when rivers run low further depletes surface water because the two are linked. Erecting dams to provide water to one group of people deprives other people and ecosystems. Leveeing up rivers and building on wetlands removes space for water to slow, pushing flooding onto neighbouring areas. Paving cities and whisking water away creates localized scarcity.

Some corporations are making 'water neutrality' or 'water positive' pledges, which are a big step forward but not enough, says Michael Kiparsky, director of the Wheeler Water Institute at the University of California, Berkeley's Center for Law, Energy and the Environment. "If corporations are really serious about water stewardship, they would throw their political and financial heft behind reform of the governance systems that set up this extractive economy around water," Kiparsky says.

More than 11,000 scientists from 153 countries agree that tweaks around the margins are insufficient. In a 2019 letter in the journal *BioScience* they called for "bold and drastic transformations", including a "shift from GDP growth and the pursuit of affluence toward sustaining ecosystems and improving human well-being"[1]. In February, the Intergovernmental Panel on Climate Change, agreed, calling for integrating "natural, social and economic sciences more strongly," in part by conserving 30–50% of Earth's ecosystems (see go.nature.com/3sccm6h).

A growing group of ecologists, hydrologists, landscape architects, urban planners and environmental engineers – essentially water detectives – are pursuing transformational change, starting from a place of respect for water's agency and systems. Instead of asking only, 'What do we want?' They are also asking, 'What does water want?'. When filled-in wetlands flood during events such as the torrential 2017 rains in Houston, Texas, researchers realized that, sooner or later, water always wins. Rather than trying to control every molecule, they are instead making space for water along its path, to reduce damage to people's lives.

Broadly speaking, the detectives are discovering that water wants the return of its slow phases – wetlands, floodplains, grasslands, forests and meadows – that human development has eradicated. People have destroyed 87% of the world's wetlands since 1700 (ref. 2), dammed almost two-thirds of the world's largest rivers[3], and doubled the area covered by cities since 1992 (ref. 4). All these have drastically altered the water cycle. The water detectives' projects – part of a global 'slow water' movement – all restore space for water to slow on land so it can move underground and repair the crucial surface–groundwater connection.

Although the uses of slow-water approaches are unique to each place, they all reflect a willingness to work with local landscapes, climates and cultures rather than try to control or change them. Slow water is distributed throughout the landscape, not centralized. For instance, wetlands and floodplains are scattered across a watershed – an area of land drained by a river and its tributaries – in contrast to a dam and giant reservoir. Around the globe, water detectives are beginning to scale up these projects.

Slow water

For most of California's state history, groundwater and surface water have been treated as separate resources from both a legal and regulatory perspective. But physically they are linked – by gravity and hydraulic pressure. When river levels run high and spill over into wetlands and floodplains, the flow slows down and seeps underground, raising the water table. Later, that groundwater feeds wetlands, springs and streams from below. "It is hydrologically ridiculous to treat groundwater and surface water differently," says Kiparsky. "That is as non-circular as you can get."

That legal separation has resulted in overtaxing California's water supply. The state's massive water infrastructure – huge dams, levees and long-distance aqueducts – prevents the great rivers of the Central Valley region from occupying their floodplains and naturally recharging groundwater. Plus, when surface water is scarce, people aggressively pump groundwater. But because the two are connected, that further decreases surface water. This depletion means that people have to drill deeper, more expensive wells to reach water. It can also collapse the land, destroying infrastructure. And pumping groundwater near the ocean can allow seawater to push salt inland.

Since passage of the 2014 Sustainable Groundwater Management Act (SGMA), California has prioritized recharging groundwater by spreading excess winter water and floodwater on land so it filters underground, or injecting it underground through wells. Various state programmes include incentives for farmers to percolate water on fallow fields, flood management that sets back levees, allowing floodplains to once again serve their purpose, and a search for palaeo valleys – special geological features that could rapidly move heavy water flows underground.

But key hurdles remain to seize the bounty of winter floods, says Kiparsky. The main problem is that, despite the SGMA, legal legacies of the artificial divide between surface water and groundwater linger. Colorado is managing this better, he says, because it has integrated the rights systems for groundwater and surface water. Connecting them legally facilitates multipurpose projects such as routing winter water to recharge ponds, which provides habitats for birds and human recreation. The water infiltrates the ground and rejoins the river, effectively making that same water available to farmers later in the year.

Peru is also focused on the connection between surface water and groundwater. Almost two-thirds of its population live on a desert coastal plain that receives less than 2.5 centimetres of rain per year and relies on water from the Andes, including from melting glaciers. In 2019, the World Bank predicted that drought-management systems in Lima – dams, reservoirs and under-city storage – would be inadequate by 2030 (ref. 5). Over the past decade, Peru has passed a series of laws that recognize nature as part of water infrastructure and require water utilities to invest a percentage of user fees in wetlands, grasslands and groundwater systems.

"If we plant the water, we can harvest the water."

One type of investment is the protection of rare high-altitude wetlands called *bofedales*, or cushion bogs, which slow water runoff that might otherwise cause flooding or landslides, and hold onto wet-season water, releasing it in the dry season. *Bofedales* are peatlands, which cover just 3% of global land area but store 10% of freshwater and 30% of land-based carbon[6]. Unfortunately, these bogs have been subject to peat thievery for the nursery trade. Utility investments are introducing surveillance to protect *bofedales* and restoring damaged wetlands. Scientists have also studied a local practice of carving out more space for water in the landscape to expand the *bofedales*, and found that these expansions can store similar quantities of water as the original bogs[7].

Peru's water utilities are also investing in a practice innovated by the Wari people 1,400 years ago. In a few Andean villages, Wari descendants still build hand-cobbled canals called *amunas*. The *amunas* route wet-season flows from mountain creeks to natural infiltration basins, where the water sinks underground and moves downslope much more slowly than it would on the surface. It emerges weeks to months later from lower-altitude springs, where farmers tap it to irrigate crops.

"If we plant the water, we can harvest the water," says Lucila Castillo Flores, a communal farmer in the Andes village of Huamantanga above the Chillón River valley in Peru. Their culture of reciprocity, with the landscape and with each other, governs how communal farmers care for the water and share the bounty. Because much of the water they use for irrigation seeps back underground, it eventually returns to rivers that supply Lima. Hydrological engineer Boris Ochoa-Tocachi, chief executive of the Ecuador-based environmental consultancy firm ATUK, and his co-researchers used dye tracers, weirs and surveys of traditional knowledge to calculate the impact of restoring *amunas* throughout the highlands. Lima already has 5% less water than its consumers need. The researchers showed that restoring *amunas* throughout the largest watershed that supplies Lima could make up that water deficit and give the capital an extra 5%, extending availability into the dry season by an average of 45 days[8].

Working with wildlife

Taking a holistic approach is also paying off in Washington state and in the United Kingdom, where people are allowing beavers space for their water needs. The rodents in turn protect people from droughts, wildfires and floods. Before people killed the majority of beavers, North America and Europe were much boggier, thanks to beaver dams that slowed water on the land, which gave the animals a wider area to travel, safe from land predators. Before the arrival of the Europeans, 10% of North America was covered in beaver-created, ecologically diverse wetlands.

Environmental scientist Benjamin Dittbrenner, at Northeastern University in Boston, Massachusetts, studied the work of beavers that were relocated from human-settled areas into wilder locations in Washington state. In the first year after relocation, beaver ponds created an average of 75 times more surface and groundwater storage per 100 metres of stream than did the control site[9]. As snowfall decreases with climate change, such beaver-enabled water storage will become more important. Dittbrenner found that the beaver's work would increase summer water availability by 5% in historically snowy basins. That's about 15 million cubic metres in just one basin, he estimates – almost one-quarter of the capacity of the Tolt Reservoir that serves Seattle, Washington.

Beavers have fire-fighting skills too, says Emily Fairfax, an ecohydrologist at California State University Channel Islands in Camarillo.

When beavers are allowed to repopulate stretches of stream, the widened wet zone can create an important fire break. Their ponds raise the water table beyond the stream itself, making plants less flammable because they have increased access to water.

And beavers can actually help to prevent flooding. Their dams slow water, so it trickles out over an extended period of time, reducing peak flows that have been increasingly inundating streamside towns in England. Researchers from the University of Exeter, UK, found that during storms, peak flows were on average 30% lower in water leaving beaver dams than in sites without beaver dams[10]. These benefits held even in saturated, midwinter conditions.

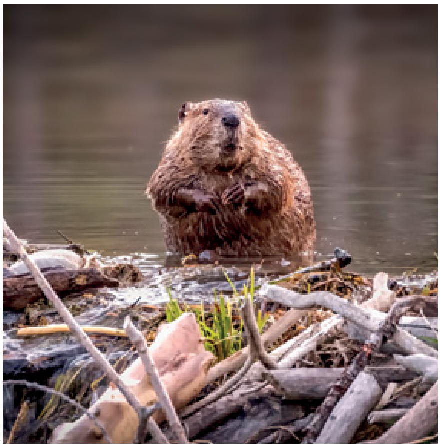
Beaver ponds also help to scrub pollutants from the water and create habitats for other animals. The value for these services is around US$69,000 per square kilometre annually, says Fairfax. "If you let them just go bananas", a beaver couple and their kits can engineer a mile of stream in a year, she says. Because beavers typically live 10 to 12 years, the value of a lifetime of work for two beavers would be $1.7 million, she says. And if we returned to having 100 million to 400 million beavers in North America, she adds, "then the numbers really start blowing up".

System change

For the most part, mainstream economics doesn't take into account the many crucial services provided by healthy, intact ecosystems: water generation, pollution mitigation, food production, crop pollination, flood protection and more.

Value calculations such as Fairfax's are increasingly tabulated by scientists but usually ignored by the market. One early effort to put a monetary value on those services was a landmark report[11] in *Nature* in 1997, co-authored by Robert Costanza, an ecological economist at the Institute for Global Prosperity at University College London. At the time, global ecosystem services were worth tens of trillions of dollars, more than global gross domestic product (GDP). In an updated paper published in 2014, the global economy had grown but ecosystem services were still worth considerably more[12].

Another problem: the degradation of those services is typically not counted against profits; instead, those costs are paid by the environment and people. Hannah Druckenmiller, an environmental economist and data scientist at the non-profit organization Resources for the Future in Washington DC, has calculated that permitting development on one hectare of wetlands incurs property damages of more than $12,000 per year[13]. That's because water that has been displaced from an area that used to absorb it floods surrounding communities.



Beavers help to protect people from floods.

TROY HARRISON/GETTY

Druckenmiller estimates the value of wetlands nationwide, just for flood absorption, to be $1.2 trillion to 2.9 trillion. And that is a conservative estimate, based on flood damage data covering just around 30% of households in floodplains.

The overarching problem is that the main measure of economic health, GDP, has a narrow focus on market-based production and consumption and does not accurately measure human well-being, Costanza asserts. "A circular economy that similarly limits itself to production will also fall short," he says. If the goal is well-being, "the question becomes: should you be producing and consuming all those things in the first place?". Protecting and restoring natural resources and rebuilding social capital, he says, are more likely to achieve well-being.

One way to do that is to put more natural ecosystems into a common asset trust, or 'the commons'. Creating state or local parks, hunting reserves, or wildlife refuges can restrict development and provide significant benefits to the community, says Druckenmiller. Communities that invest in protecting a wetland to prevent flood damages will see the benefit of avoided costs quickly, she says, often with a payback period of less than five years.

Another strategy to protect the commons, says Costanza, is the 'rights of nature movement', which began in the early 1970s and has gained ground over the past 15 years. It includes enshrinements in the constitutions of Bolivia and Ecuador, local government changes across the United States, and personhood for the Whanganui River in New Zealand, the Ganges River in India and the Magpie River in Canada. That might sound unusual to some people, but in the United States, some corporations have personhood. Granting personhood to a river enables people to argue in court on behalf of its rights. A river's rights can include freedom from pollution, protection of its cycles and evolution, and space to fulfil its ecosystem functions. The rights of nature movement recognizes that healthy ecosystems make everything work, and "people are part of that system and not separate from it", says Costanza.

States reforming century-old water rights, utilities investing in wetlands and Indigenous techniques and scientists deploying beavers for their engineering prowess are definitive shifts from business as usual. "We've made a lot of progress integrating [natural capital] into the system, where it doesn't get pushed aside because other things are higher priority," says Druckenmiller.

But Costanza thinks much deeper change is needed. "A lot of the things that we're talking about with the circular economy — regenerating wetlands, planting forests, dealing with climate change — are difficult to implement because the underlying goal is still GDP growth, and these things get in the way of that," he says.

People applying slow-water approaches are doing what they can in the dominant economy. But Costanza says that people can better protect social capital and environmental systems by switching from GDP to metrics such as the Genuine Progress Indicator or one of "literally hundreds" of alternatives, he says.

Society's fundamental goals might seem like a high bar to set, but some of these metrics have already been adopted by governments in Maryland, Vermont, Bhutan and New Zealand. Such shifts move beyond greenwashed versions of a circular economy and help to facilitate water detectives' work in caring for water systems so that they can sustain human and other life.

Erica Gies is a journalist based in San Francisco, California, and the author of *Water Always Wins: Thriving in an Age of Drought and Deluge* (Univ. Chicago Press, 2022).

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NUSEED

Carinata is a crop that produces an energy-rich oil and can help to sequester carbon.

The biofuel course correction

Refineries that convert biomass to energy are expanding. Attention must be paid to how feedstock crops change soil carbon. **By Peter Fairley**

Russia's invasion of Ukraine is squeezing global oil supplies and inflation is jacking up prices at the pumps. Although petrol prices have started to fall in recent months, the situation has delivered a powerful reminder of the world's dependence on fossil fuels.

It also means biofuels are having a moment. The corn-ethanol industry boasts that blending its product into petrol is saving consumers money and creating jobs in the farming communities that supply its distilleries.

Refiners producing renewable diesel fuels for long-distance lorries are expanding as fast as they can. Some are building biorefineries designed to process palm, soya and canola oils, whereas others are adding vegetable oils and animal fat to their petroleum feedstocks. Petrochemical producer Phillips 66 is investing US$850 million in its refinery in Rodeo, California, to convert it to exclusively process bio-feedstocks. And, according to market analysts, US refinery expansions that have been announced could boost the demand from biofuel manufacturers for soya bean oil beyond the country's total supply. If filling fuel tanks with these plant-derived liquids reduces carbon emissions by decreasing the demand for fossil fuels, it would help to tackle the climatic shifts that threaten humanity and biodiversity.

In principle, the sustainability of biofuels seems obvious. Carbon cycles in and out of the atmosphere as biofuel crops grow and vehicles burn the fuel they produce. But claims by industry that biofuels deliver greener transport have been battered by a relentless flow of reports. Indeed, the first-generation biofuels that are the market leaders seem to be little better for the climate than fossil fuels. A 2022 assessment[1] of the US Renewable Fuel Standard found that the programme — which requires that transportation fuel contain a minimum volume of renewable fuel, and which drives nearly half of global biofuel production — has probably increased greenhouse-gas emissions. That counter-intuitive outcome is a result of farm operations involving diesel-fuelled tractors and fertilizers made from natural gas. The fertilizers release nitrogen oxide, a greenhouse gas that is nearly 300 times more potent than carbon dioxide. Even farm soils can release stored carbon that is essential to their resilience and fertility.

Worse still, the increase in demand for biofuel crops has extended farming onto marginal lands, damaged biodiversity and increased water use and contamination, as well as pushed up the price of agricultural commodities and thereby exacerbated food insecurity. The authors of the 2022 assessment conclude that only "profound advances" in practice and policy will make the US programme sustainable.

Agronomists, crop geneticists and carbon emission life-cycle scientists agree. To make agriculture smarter, farmers need to pay close attention to what crops work best where, and how those crops are grown. Embracing regenerative farming methods, such as reduced tilling of the soil, can retain carbon and nutrients. So, too, can planting an emerging set of winter oilseeds that can be grown seasonally between food-crop rotations. This would generate revenues that could pay for a soil-saving practice called cover cropping that few farmers have embraced so far.

"We cover crop less than 2% of our land. If you go to 40–50%, you're meeting this huge global demand for low-carbon feedstocks," says Glenn Johnston, referring to the process of growing a crop to protect and improve the soil — a crop that, in this case, can also be used to make biofuel. Johnston leads regulatory and sustainability programmes for agribusiness firm Nuseed at its research centre near Sacramento, California.

Despite this promise, the new era of biofuels still poses environmental concerns. Researchers argue that regulation needs to be much improved to ensure that the industry arcs towards sustainability. Tracking carbon is a complex process full of pitfalls. Get it wrong and biorefineries could end up as one more environmental panacea that bites the dust.

Digging deeper

A decade ago, a transition to better biofuels seemed imminent. A new generation of commercial-scale biorefineries was coming online in the United States, Brazil and Europe. They were designed to make ethanol from fibrous cellulose-rich feedstocks such as agricultural leftovers, grasses or fast-growing trees that generally thrive on marginal farmlands and require less intensive cultivation than corn or soya beans. By now, these cellulosic biofuels made from sustainable feedstocks were supposed to be gushing into the fuels market, trimming transport emissions — the fastest-growing source of CO_2 worldwide.

Alas, the flow of cellulosic fuel is barely a trickle. Processing equipment proved hard to operate, petrol prices fell and governments eased mandates designed to force the pricier cellulosic fuels into the market. “Ultimately all of those facilities struggled. Most are either producing at very low levels today or not producing at all,” says John Field, who studies the climate mitigation potential of bioenergy systems at Oak Ridge National Laboratory in Tennessee.

What didn’t stop were the generous incentives pushing food-based biofuels, and their shortcomings. Europe’s renewable energy directive drove logging and slash burning of tropical rainforests in Brazil, Indonesia and elsewhere to make way for soya bean and oil palm plantations, displacing Indigenous communities and wildlife and releasing the rainforests’ massive carbon stocks. And the carbon does not only come from the trees; even more can be released from soil as it heats up and dries. Indeed, soil holds roughly three-quarters of the organic carbon in Earth’s biosphere.

Newer programmes that tie biofuel incentives to their carbon intensity, such as California’s low-carbon fuel standard, still fail to prevent unintended consequences that can come from a change in land use, says Ben Lilliston, director of rural strategies and climate change at the Institute for Agriculture and Trade Policy in Minneapolis, Minnesota. Demand for feedstocks can release carbon that is stored in forests and farm soils in ways that regulators struggle to factor in. For instance, in the past five years or so, US biorefineries have bought a growing share of US soya bean harvests. This can indirectly bump up carbon releases because soya bean producers elsewhere scale up to meet US soya demands.

The resulting carbon debt might never be repaid. According to a 2020 study[2], once land-use impacts are taken into consideration, the carbon intensity of palm oil-derived biofuels is triple that of petroleum fuels.

Farming to supply biorefineries also imposes an opportunity cost because, in many cases, restoring the same land to forest or native grasses would offer greater net carbon reduction. “The typical analysis of biofuels in effect ignores this cost — it treats land as free, from a climate perspective,” says Tim Searchinger, the technical director of the food programme at Princeton University’s Center for Policy Research on Energy and the Environment in New Jersey.

The land-use and life-cycle studies required to fully account for a biofuel’s carbon footprint or saving are complex and expensive — and can yield inconvenient results for biofuels producers. Furthermore, finding reliable data isn’t easy. Soil carbon, for example, varies greatly across short distances. And variability over time means it can take up to a decade before sampling detects important changes in soil carbon. “It’s time-consuming and costly to do it right,” says Rebecca Rowe, who studies soil carbon at the Centre for Ecology and Hydrology in Lancaster, UK.

That makes assessing biofuel sustainability “daunting” according to Pedro Piris-Cabezas, director for sustainable international transport based in London at the Environmental Defense Fund. “It quickly becomes crazy,” he says. But Piris-Cabezas thinks that tools and methods exist to reliably cut through the complexity, and these will show that some biofuels do reduce carbon emissions without degrading ecosystems and communities. Piris-Cabezas has written a handbook (see go.nature.com/3s6hco2) on tracking methods that can ensure that alternatives to aviation fossil fuels have “high integrity”.

“We will always be balancing impacts against the needs of society.”

Piris-Cabezas is less confident, however, that such rigorous analysis will show that biofuels can be produced sustainably at large scale. And he is pessimistic about their economic viability, thanks to an emerging challenge from another class of alternative fuels: electrofuels, produced through renewable electricity and hydrogen. Piris-Cabezas predicts that in the next decade, the cost to avoid a tonne of CO_2 emissions through the use of electrofuels will fall to about $70. Cutting a tonne of carbon using current biofuels costs $300–$400, he says, and that cost is likely to rise.

The ultimate dilemma regarding biofuel is intensified competition for finite land. The World Resources Institute, a sustainability think tank in Washington DC, projects a 56% gap between food calories produced in 2010 and those needed in 2050 (see go.nature.com/3tknoy3). At the same time, most mitigation pathways that limit global warming in keeping with the Paris climate agreement require an outright reduction in agricultural land use. Expansion of biofuel production will, therefore, inevitably drive up food prices and worsen food insecurity, says Janet Ranganathan, who studies environmental accounting and technology and oversees research at the World Resources Institute. She doubts that future advances can secure more than a niche role for biofuels: “The prospects for improvement are limited unless the need for dedicated land to grow them is eliminated.”

Cover for carbon

In spite of powerful headwinds, researchers continue working to improve biofuels’ sustainability. “Short of returning land to a completely wild state, we will always be balancing impacts against the needs of society,” says Rowe, whose work is helping the UK government to implement plans to expand the planting of bioenergy crops from close to nothing to about 3% of the UK’s land area by 2050.

And Field’s research suggests that biofuels still have the potential to be more than a necessary evil. In a 2020 paper[3] he and his colleagues showed through simulation that, under certain conditions, cellulosic ethanol can rival or exceed the climate benefits of ecosystem restoration. The best results occurred for the case of land use transitioning from food crops or pasture to the cultivation of switchgrass (*Panicum virgatum*), a popular feedstock for cellulosic biofuel. In those cases, Field and his co-authors estimated that the carbon mitigation potential was comparable to that for reforestation. If crop yields and bioprocessing technologies can be improved, and if CO_2 from biorefineries can be permanently sequestered deep underground, the researchers predict that supplying cellulosic feedstocks could ultimately store up to four times more carbon than does reforestation. “It’s aspirational, but these are areas where there’s a lot of research and development attention right now,” says Field.

Companies are already developing CO_2 pipelines in North Dakota and Illinois, and they’re in line for enhanced tax breaks under the US Inflation Reduction Act that was passed in August. Of course, these companies also face significant pushback, including from farmers whose land might be in the pipelines’ path.

For the UK bioenergy crop scale-up, Rowe says *Miscanthus* (a crop akin to switchgrass) and other perennial feedstocks are the preferred option. The UK government expects that these crops will help to cut emissions from biorefineries by the 2030s — especially when coupled with deep sequestration. The key, says Rowe, is to use the lessons learnt from biofuels development to work out the most

STEVE PROEHL/GETTY

The petroleum company Phillips 66's oil refinery in Rodeo, California.

sustainable places to cultivate. That generally means avoiding high-carbon soils such as peatlands, biodiversity hotspots and high-value agricultural croplands.

The best candidates for sustainability are the cover crops in development that seem to be a good response to arguments against dedicating land to biofuels. Soil in fallow fields tends to compact, and is susceptible to erosion by wind and rain. A cover crop puts roots down to secure the soil and its nutrients, and creates channels that help water to sink in rather than drain off. Farmers might be convinced to plant oilseed cover crops because the crop can pay for itself by producing oils that can be supplied to biorefineries.

Nuseed's crop carinata – adapted from *Brassica carinata*, a towering cousin of rapeseed (*Brassica napus*) – produces an energy-rich, inedible oil. And it packs a punch: Johnston says carinata excels at storing carbon in soil and contains about 2.5 times more oil than soya beans, the dominant crop for renewable diesel. Most importantly, he says, carinata does not compete with food supplies or cause climate-harming land-use changes. The latter advantage means that although land-use effects alone add an extra 4–26 grams of CO_2 emissions per megajoule of energy delivered from soya-based fuels, according to Field, carinata cuts 9–13 grams of emissions per megajoule from fuels. "Land-use change goes from being a highly uncertain but potentially large liability to having a small-but-positive effect," says Field, who is part of a consortium partnered with Nuseed on carinata research and development.

A 2022 report[4] by Field and his colleagues shows that carinata could support a major biofuels industry in the southeastern United States. Simulating application of carinata every third year across southern Georgia, southern Alabama and northern Florida – a few percent of US cropland – they project annual harvests exceeding 2 million tonnes. That's enough seed to make about one billion litres of aviation fuel.

The push for rigorous rules

Nuseed started commercial planting in Argentina in 2019 and is sending enough oilseed to the French biofuels producer Saipol this year for the company to generate millions of litres of renewable fuel. Nuseed plans to expand to the southeastern United States by the end of this year and to Brazil by 2024. It intends to scale up fast thereafter, aided by a ten-year supply and market-development deal with energy giant BP, and to be supporting billions of litres of fuel production per year by 2030.

For carinata to occupy a larger role in the biofuels scene smarter policies are needed, says Johnston. Government programmes for biofuels, he says, lack the breadth and specificity to recognize and reward the crop's benefits.

Lilliston concurs, in that refineries selling soya-derived fuels to California pay no penalty for soil carbon depletion caused by industrial farming practices, he says. California and other jurisdictions are planning more sophisticated carbon accounting, but not fast enough for oilseed cover crop developers.

What's racing forwards instead are poorly regulated markets for offsetting carbon – financial instruments that threaten to give regenerative agriculture a bad name. Offsets pegged to soil carbon, created by brokers as well as some agricultural giants, pay farmers to adopt carbon-friendly practices. Corporations purchase most of the offsets to claim progress towards emission reduction pledges such as 'net-zero by 2050'.

These offset markets, however, often ignore the pitfalls associated with carbon accounting, and lack the rigour required for accurate soil carbon measurement. Many offset markets stipulate that soil sampling needs to go to a depth of only 30 centimetres, despite research showing that reliable accounting requires sampling across a crop's full root zone, which could extend down to one metre or more. Some markets also allow contracts requiring farmers to maintain climate-positive practices for as little as five years, after which it might not be clear whether carbon stores have risen or fallen, let alone by how much.

One big concern is that the benefits of soil carbon offsets, including those associated with cover crop biofuel feedstocks, could turn out to be illusory and thereby undermine the integrity of net-zero targets. These offsets could also encourage lobbying for weaker government rules as regulators catch up. "People buying up cheap soil carbon offsets with questionable accounting methodologies have a vested interest in making sure that tomorrow's regulations don't dissolve their offsets' value," says Ranganathan.

Indeed, these markets might also help to perpetuate the extractive culture that dominates agriculture today. Farmers depend on agribusiness giants and fossil-fuel providers for products such as fuel, fertilizer and seed, and they struggle to make ends meet because those big firms capture most of agriculture's economic value. The balance could tilt even further if farmers are also relying on those corporations' offset programmes to recoup the value of regenerative crop production.

Advocates for farming communities are instead calling for a complete overhaul of the agricultural ecosystem that gives more back to these communities – a system that, as Lilliston puts it, "circulates both natural and economic resources to create a more sustainable and resilient system".

But a ground-up revamp for agriculture is a big ask. If the sustainability of biofuels depends on such fundamental changes, one has to wonder whether another next-generation biofuels failure isn't the more likely outcome.

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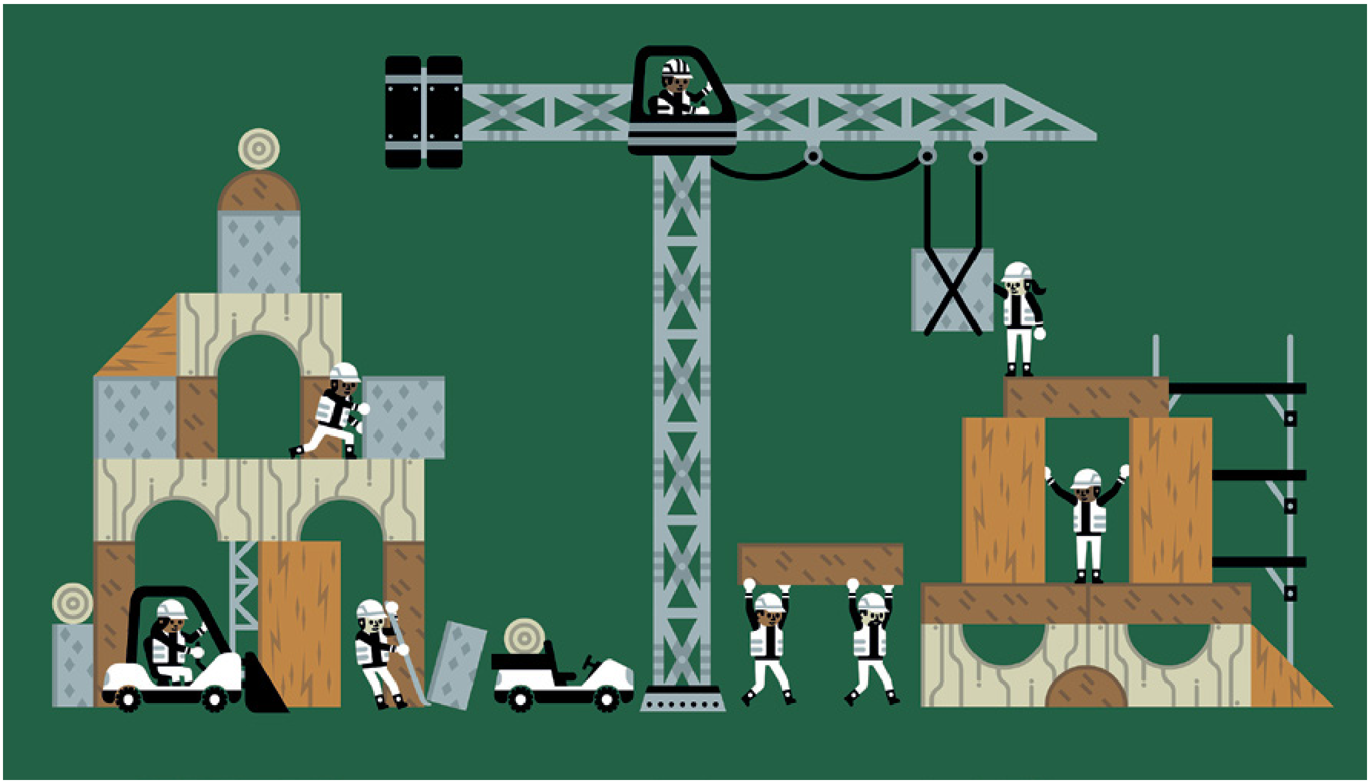


ILLUSTRATION BY JAN KALLWEJT

Greener buildings

The built environment provides a huge opportunity to move to a circular economy. Standardization, along with smart design and implementation, will be key to enabling the shift. **By Katharine Sanderson**

Our built environment — from houses to offices, schools and shops — is not environmentally benign. Buildings and the construction industry are, in fact, the world's biggest consumer of raw materials and contribute 25–40% of global carbon dioxide emissions (F. Pomponi & A. J. Moncaster *Clean. Prod*. **143**, 710–718; 2017). Making buildings part of a circular economy that minimizes the waste of materials could therefore yield huge environmental rewards. Conversely, failure on this front could have dire consequences.

"Buildings can, and must , work in a circular way," says Francesco Pomponi, who studies the built environment at Edinburgh Napier University, UK. "Otherwise, there's no way out of the climate crisis."

Take concrete, made by mixing gravel, cement and water. It is the world's most widely used building material, yet it is also a huge carbon source, accounting for up to 8% of global human-made carbon emissions. Cement, more than four billion tonnes of which are made each year, is the biggest contributor. Its production requires limestone (primarily composed of calcium carbonate) to be heated to yield lime (calcium oxide). The reaction releases CO_2, and yet more CO_2 is produced by fuel combustion to generate the heat.

Buildings as a positive force

Across the globe, engineers, construction companies and architects are beginning to embrace and apply the circular model. There are ample opportunities to improve the materials that are used in construction, to introduce circular design principles so that those materials can be properly repurposed, and — even more ambitiously — to create buildings that make a positive contribution to climate and biodiversity. But much work needs to be done if those huge contributions to emissions are going to come down. And come down they must — fast.

Innovations in materials could help to make concrete a more sustainable option. Adding graphene — a 2D form of carbon — into the mix, for example, might improve the environmental footprint by strengthening concrete and thus reducing the amount needed for a particular application. Sprinkling it into concrete could bring enormous benefits, according to Nationwide Engineering, a company based in Amesbury, UK, that developed this mixture, called Concretene, in collaboration with researchers at the University of Manchester, UK. The first building to benefit from Concretene was a gym in Amesbury in May 2021, which had a new floor laid using the material.

Concrete could even become a carbon sink. CarbonCure, a company based in Halifax, Canada, has developed a technology that adds captured CO_2 into concrete. The CO_2 reacts with the calcium in the mixture to form calcium carbonate, a mineral that the company says adds strength to the concrete as well as locking in carbon.

Concrete is already commonly repurposed – waste concrete is crushed up to form recycled concrete aggregate (RCA), which can then be used to make new aggregate. But RCA tends to be used in low-tech applications, such as filling in roads. This reduction in the quality and value of concrete doesn't fit well with a fully circular economy.

CarbonCure is developing a new type of RCA that can be used in buildings. Sean Monkman, who heads technology development at the company, says that the same CO_2-injecting technology, and subsequent mineralization, can be applied to RCA as well as freshly made concrete. Another company, Blue Planet Systems, based in Los Gatos, California, has developed an RCA made from recycled waste concrete and incorporating captured CO_2.

At the Georgia Institute of Technology in Atlanta, the Kendeda Building for Innovative Sustainable Design uses CO_2-storing concrete as one of a suite of sustainable innovations. The Kendeda project was built as part of the Living Building Challenge (LBC), a programme that allows the designation 'living building' to be applied to construction projects that meet a range of criteria, from responsible water use to sourcing materials that eliminate waste. The programme aims to provide an incentive for buildings to generate energy, produce their own water and give back to nature more than they take, says Kendeda Building director Shan Arora. There are 83 certified Living Building projects globally, with another 241 projects registered to pursue certification.

In trying to meet the LBC criteria, the Kendeda construction team salvaged materials by using local labour to intercept them as they were about to reach landfill sites, and then turned them into suitable feedstock. "During the construction process, the Kendeda Building diverted more waste from the landfill than it sent to the landfill," says Arora.

The LBC project is hugely ambitious. "I view the LBC as a sort of holy grail for regenerative building design," says Nick Jeffries, who specializes in building innovations at the Ellen MacArthur Foundation, a charity based in Cowes, UK, devoted to furthering the circular economy.

There are less ambitious, but still useful, steps that can be taken alongside more holistic and demanding projects. In a rapidly warming climate, even windows can make a difference. In 2010, the iconic Empire State building in New York City underwent a radical refit, including an upgrade to all of the skyscraper's 6,514 windows. The existing panes, rather than being ditched, were each taken out, and the gap in the double glazing was filled with an insulating gas – a mixture of argon and krypton. In addition, each pane was coated with a light-filtering clear film. These films, developed by scientists at the Massachusetts Institute of Technology's Lincoln Laboratory in Lexington in the 1970s (J. C. C. Fan *et al. Appl. Phys Lett.* **25**, 693; 1974), and now sold by the Eastman Chemical Company, headquartered in Kingsport, Tennessee, use nanometre-sized metal particles to reflect heat. The refurbished windows resulted in the Empire State Building consuming 40% less energy. Similar refits in other buildings will be crucial in a transition to circular construction, says Jeffries.

Dismantling the problem

In a circular economy, Jeffries says, "Buildings should be built like Lego. You should be able to disassemble them and reuse the structural elements."

Pomponi agrees that design is key, and that applying existing techniques thoughtfully can allow for buildings to incorporate such flexibility. For example, rather than welding steel frames together to form the skeleton of a building, bolts can be used instead. "This enables much easier disassembly when the useful life comes to an end, and much easier reuse of the structural section," Pomponi says.

"Even when materials with a low environmental impact are used, a building can be designed in a non-circular way," says Caroline Henrotay, a former coordinator of the Buildings as Materials Banks project (BAMB), a Horizon 2020 innovation project funded by the European Union. If materials are, for example, glued together, Henrotay explains, "it will be more difficult to create clean fractions for high quality recycling at the end of life".

Such mechanical construction approaches are key to Wikihouse, a BAMB-supported UK project that provides the open-source design for blocks that can be cut locally from birch plywood, allowing buildings to be assembled by slotting the pieces in place as in a jigsaw puzzle, and to be taken apart again easily. The approach has been used to build places such as libraries across the globe and houses in Almere, the Netherlands.

This kind of reuse has an ancient legacy, says Jeffries. "The theatre of Marcellus [in Rome] is still going after 2,000 years," he says. "It was used even as a quarry to build local bridges and roads. It was really a material bank for future buildings."

One modern-day tool to keep track of the components of a building – and ensure that they can be reused in a meaningful way – is a 'materials passport'. This document contains a detailed inventory of what materials were used, plus any data to do with safety or the origin of the material. With all this data collated, the components become a useful commodity at the end of that building's life. A materials passport makes it easy to design a follow-up building, because the component specifications are known exactly in advance. The passport, Jeffries says, "acknowledges that the material exists in a particular structure, and then identifies the most useful future destination". He points to an example of a building with such a passport that has already been dismantled for reuse: the Temporary Courthouse Amsterdam, which was moved to a business park outside the city of Enschede in early 2022 to become an office building.

Coordinated material tracing

A number of start-ups are emerging to offer materials-passport services, but this could lead to confusion in future. The LBC has a vision that is broader than simply having a materials passport, says Arora. The LBC also has a growing list of unsafe materials, the Red List, that must be avoided, such as asbestos, formaldehyde and chlorinated polymers, because they are damaging to human and environmental health. To be permitted in an LBC building, materials need to be listed and accounted for and also meet specific criteria. Given the range of ongoing projects, ambitions and definitions around the circular economy for buildings, its global adoption will take time. "I'm still figuring out who owns the circular-economy transition," says Pomponi.

Wholesale take-up of circular-economy practices will require enough decision makers to think not only that such measures will help the planet, but that they will be economically feasible. "We need everyone. We need the Apples, the Googles, the Microsofts of the world to prove that this can be done," Jeffries says. With more than 200 companies in the Ellen MacArthur Foundation's network, Jeffries wants to see them move beyond the shorter-term goals. "We can go beyond doing less harm," he says, and progress to the more affirmative goal of "reducing the materials we use, reducing emissions, reducing the waste generated, to buildings actively cleaning the air, providing habitats for wildlife".

Such ambitious advances in building design and construction will be essential to a sustainable global economy. Ultimately, the buildings that shelter and protect humanity will need to do more than offer a roof over our heads: by embracing innovative methods and materials, buildings could become a solution to the climate catastrophe that humans have invited.

Katharine Sanderson is a science journalist based in Cornwall, UK.

MIKKO RASKINEN

Recycling cellulose involves producing a pulp that can then be used to make new fibres.

New yarn from old clothes

Chemical processes could recycle the cellulose from textile waste into renewed fibre for garment makers.

By Neil Savage

Sonja Salmon is a big fan of cellulose, and that's why she wants to destroy it. "I love cellulose," she says. "I'm ripping cellulose apart because I love it."

She's also pulling it apart because the polymer, which is found naturally in wood and cotton, accounts for one-quarter of all the fibres used in textile manufacturing. That means any effort to recycle clothing and fabric to keep them part of the circular economy for as long as possible has to include ways to deal with all that cellulose.

Salmon, a polymer scientist at Wilson College of Textiles, North Carolina State University in Raleigh, is working on breaking down the cellulose from discarded textiles and reusing it. Many clothing fabrics are a blend of half polyester and half cotton – individual fibres of cotton and polyester are twisted tightly around one another, creating a yarn that is then woven or knitted into a garment. Taking that structure apart mechanically is challenging, so instead Salmon treats it with cellulases, a group of enzymes that break up the cellulose. "We can chew it up into small enough molecules and fragments that it will actually fall out of the rest of the fabric structure," Salmon says.

Her focus is on characterizing the material that comes out of the breakdown process and working out what it might best be used for. For example, the enzymes break down the cellulose into glucose, which could be used as a feedstock for making biofuel. They also leave behind tiny chunks of cotton fibre that could provide lightweight reinforcement for concrete. "Even though the cotton fibre will no longer be long enough to directly spin it back into a yarn, we think the material has value," Salmon says.

This way of thinking is a big change from how old clothing and textiles, such as upholstery fabrics and carpeting, are currently handled. Globally, only 13% of the material that goes into making clothing is recycled, according to the Ellen MacArthur Foundation, an organization in Cowes, UK, that promotes the circular economy. Most textile waste – an estimated 92 million tonnes from the fashion industry alone – produced each year winds up buried or incinerated. "We throw stuff away into landfill and we're treating it like garbage," Salmon says. "We're not looking upon it as something that is actually a raw material that could be reused." The US Environmental Protection Agency estimated that, in the United States in 2018, the average person threw away 47 kilograms of textiles. About three-quarters of that – 36 kg – is clothing and footwear, while the rest is mostly towels, bedding, furniture fabrics and carpets. Meanwhile, resources are expended to create virgin material (see 'Thread count') – water and land to grow more cotton, and petroleum to make more polyesters (see 'Recovering polyester').

To counter all that waste, researchers and start-up companies are developing methods to recover and reuse the material. Similar to Salmon, much of their focus is on chemical recycling, in which the material is broken down into its building blocks and used to create new materials, including fibres that can be woven into new clothes. The challenges lie in developing the processes for such treatment. They have to be practical, but they also have to be at least as cost-effective as simply making new fibres.

Spinning new threads

In addition to the natural cellulose fibres from cotton, some textiles include human-made cellulosic fibres. These fibres are derived from wood-pulp cellulose and can be used to make materials such as viscose (rayon) and a similar material called lyocell. Cellulosic fibres make up around 6% of all textile fibres produced, according to the Textile Exchange in Lamesa, Texas – a non-profit organization that promotes environmentally friendly materials.

A variation on the lyocell-manufacturing process is being applied to the textile-waste problem by Evrnu, a start-up in Seattle, Washington. One major change the company has made to the process is it uses discarded textiles, instead of wood, as the source of its cellulose. Its also tweaked the process to produce a fibre that the firm's co-founder and president Christopher Stanev says is superior to both other cellulosics and to cotton, and that can be recycled more times. "We can make much stronger fibre using cotton than the one coming from wood pulp," says Stanev, a textile engineer.

In the same way as the standard lyocell process, the raw material is treated with *N*-methylmorpholine *N*-oxide (NMMO), an organic compound that dissolves cellulose. This produces a thick pulp that is then filtered. At this point, the conventional process would involve the cellulose being extruded through a device called a spinneret – first into air, and then into a coagulation bath of mostly water in which the material solidifies into fibre. Evrnu, however, turns the cellulose molecules into liquid crystals before they are extruded, allowing them to align with each other and produce a more crystalline fibre structure.

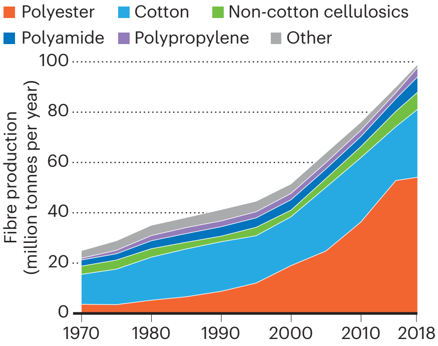
"By doing that and having quite a crystalline organization, you can increase the strength and you can also engineer the performance of this fibre," Stanev says. He says the fibre is about 20% stronger than standard lyocell, which itself is stronger than cotton.

That quality translates into a longer lifetime for a fabric made from the fibre, as well as a fibre that can be reconstituted several times. Every time the molecules are run through the recycling process, they become shorter and thinner. But because they start out stronger, Stanev says, the same material should be able to be reconstituted at least five times before it becomes weaker than virgin cotton fibre; some tests in the company's laboratory show that the material can be recycled up to ten times. That's more than is possible for paper, which can be recycled 5–7 times before the fibres become too short to make a viable new product.

Evrnu is running a pilot project at partner companies in Germany and elsewhere in the United States to show that its process can produce fabric. It hopes that a larger textile company will then want to license the technology. For now, it is using NMMO because the compound is readily available, but Stanev hopes to eventually switch to an ionic liquid – a salt that is liquid below 100 °C – which is more chemically stable than NMMO and more tolerant of contaminants. The firm has not yet optimized any such liquids for the production process.

THREAD COUNT

Globally, clothing consumption, and, therefore, textile production, has increased since the 1970s. The rise in polyester production has been the most marked.



SOURCE: K. NIINIMÄKI *ET AL.* *NATURE REV. EARTH ENVIRON.* 1, 189–200 (2020).

A Finnish company, however, is working with an ionic liquid developed by one of its founders, physical chemist Herbert Sixta at Aalto University in Espoo, Finland. The liquid used by Ioncell – the name of both the company and the process – is a superbase, a highly alkaline substance that breaks the hydrogen bonds in the cellulose molecules. In the same way as when using NMMO, that process creates a pulp that can be fed through a spinneret to make a new cellulose fibre. NMMO tends to be unstable and requires the addition of buffer solutions, but the ionic liquid does not. Sixta says his ionic liquid is also completely recyclable, making the process environmentally friendly as well as producing fibres with better mechanical properties than cotton.

The Ioncell process can use wood pulp, which Sixta says counts as part of a circular economy because the raw material comes from Finland's sustainable forests – these are managed in such a way that growth outpaces the amount removed. "Our university has a large group in textile design, so we can treat wood, produce pulp, convert it to fibres, convert it to yarns, convert it to fabrics, design clothing, and show the clothing in fashion shows," Sixta says. The process can also accept textile waste, turning old clothing into new garments. Ioncell has built a pilot plant, with the goal of evaluating how well its process works in the real world in about two years.

A matter of cost

Although technical challenges abound, the main barrier to widespread textile recycling might be economic, says materials engineer Youjiang Wang at the Georgia Institute of Technology in Atlanta. "Most of the materials are not that valuable," Wang says. It's so cheap to produce polyester, cotton and other fabrics that there's little profit margin unless the recycling processes are very inexpensive.

There's also a lack of infrastructure for collecting and sorting used textiles, beyond a few private clothing-donation groups. And the complex mixture of materials in a piece of clothing – not just different natural and synthetic fibres, but also dyes and chemical coatings, buttons and zips, and any non-woven additions such as leather or latex – must be separated for individual components to be processed.

Policymakers should consider recycling that turns used clothing not into new clothes but into other useful – if lower value – products, Wang argues. Fibres might be shredded for use as soil stabilizers, for instance, or cellulose broken down into glucose that can be turned into fuel. Even burning polyester for energy is preferable to pulling more petroleum out of the ground to produce power. "That doesn't sound very high tech, but overall, you do get considerable benefit from that," Wang says.

The circular economy should be viewed as a way to reduce as much as possible the creation of virgin material when other products can be reused, Wang says. "If you really want to make recycling better for the environment, not just for the sake of publicity, then we need to develop more technologies so that you can use as much of what you collect as possible," he says. "That would make the overall circle more circular."

Neil Savage is a freelance writer based in Lowell, Massachusetts.

RECOVERING POLYESTER

Cellulose isn't the only polymer researchers want to reuse — they also have polyester in their sights.

Polyester is a generic term for a range of polymers derived from petroleum, but it mainly refers to polyethylene terephthalate (PET). Globally, PET polyester makes up around half of all fibre in all textiles. Cotton comprises another one-quarter and the rest consists of other plant-based fibres, such as linen and hemp; animal products, such as wool and alpaca; other synthetics, including acrylic and nylon; and human-made cellulosic fibres.

Like cotton, PET polyester can be spun into new fibres, but the re-spun fibres become shorter and weaker with repeated cycles. Unlike cotton, however, the polymer could be broken down into the simpler molecules that make it up and those monomers could then be reconstituted into new polymers. Starting with waste PET, Sonja Salmon, a polymer scientist at North Carolina State University in Raleigh, says, it's possible to create what is essentially a virgin material — one that is indistinguishable from PET made from petroleum. PET is extremely stable, however, so reducing it to monomers is difficult.

Some scientists are developing enzymes that might be able to tackle these molecules. In 2016, a team discovered a bacterium that could break down PET (S. Yoshida *et al.* *Science* **351**, 1196–1199; 2016), and scientists have since developed other enzymes to degrade it (J. Egan & S. Salmon *SN Appl. Sci.* **4**, 22; 2022). Christopher Stanev, co-founder of Evrnu in Seattle, Washington, says alongside its main focus of breaking down cellulose, the start-up is also working on processes to break down PET and polyurethane, and to separate polyester–cotton blends.

outlook

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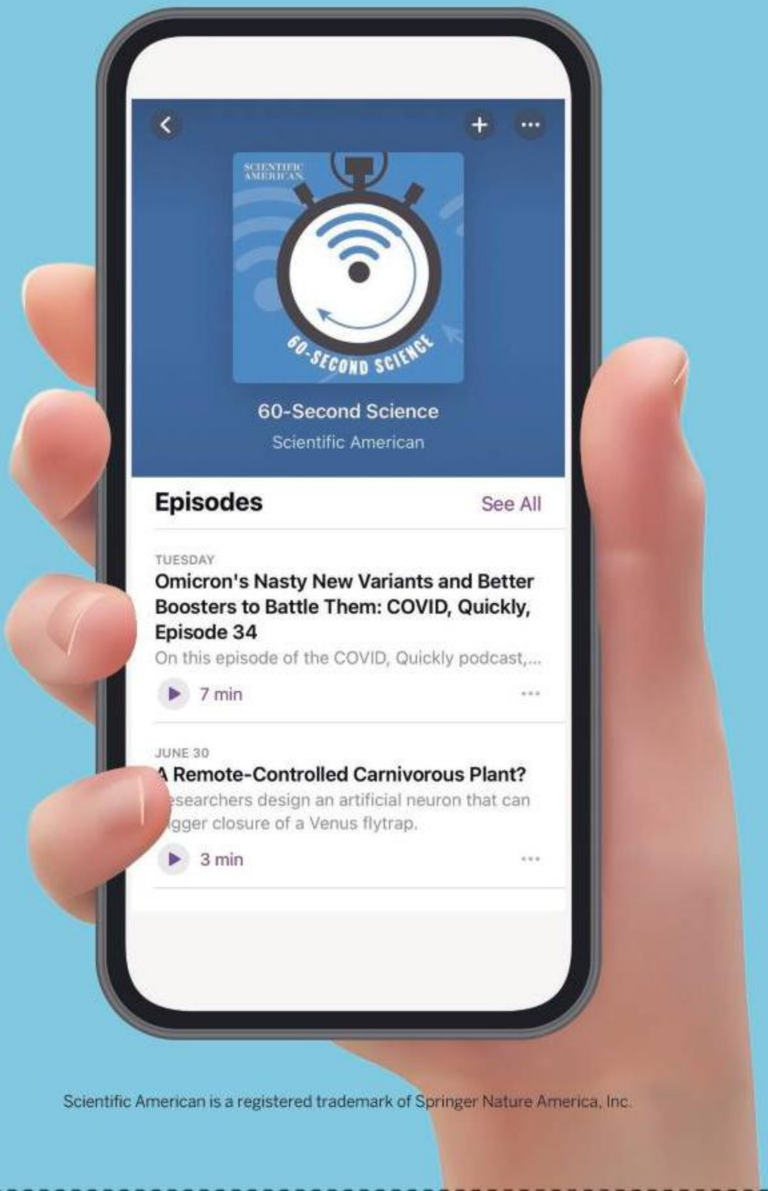

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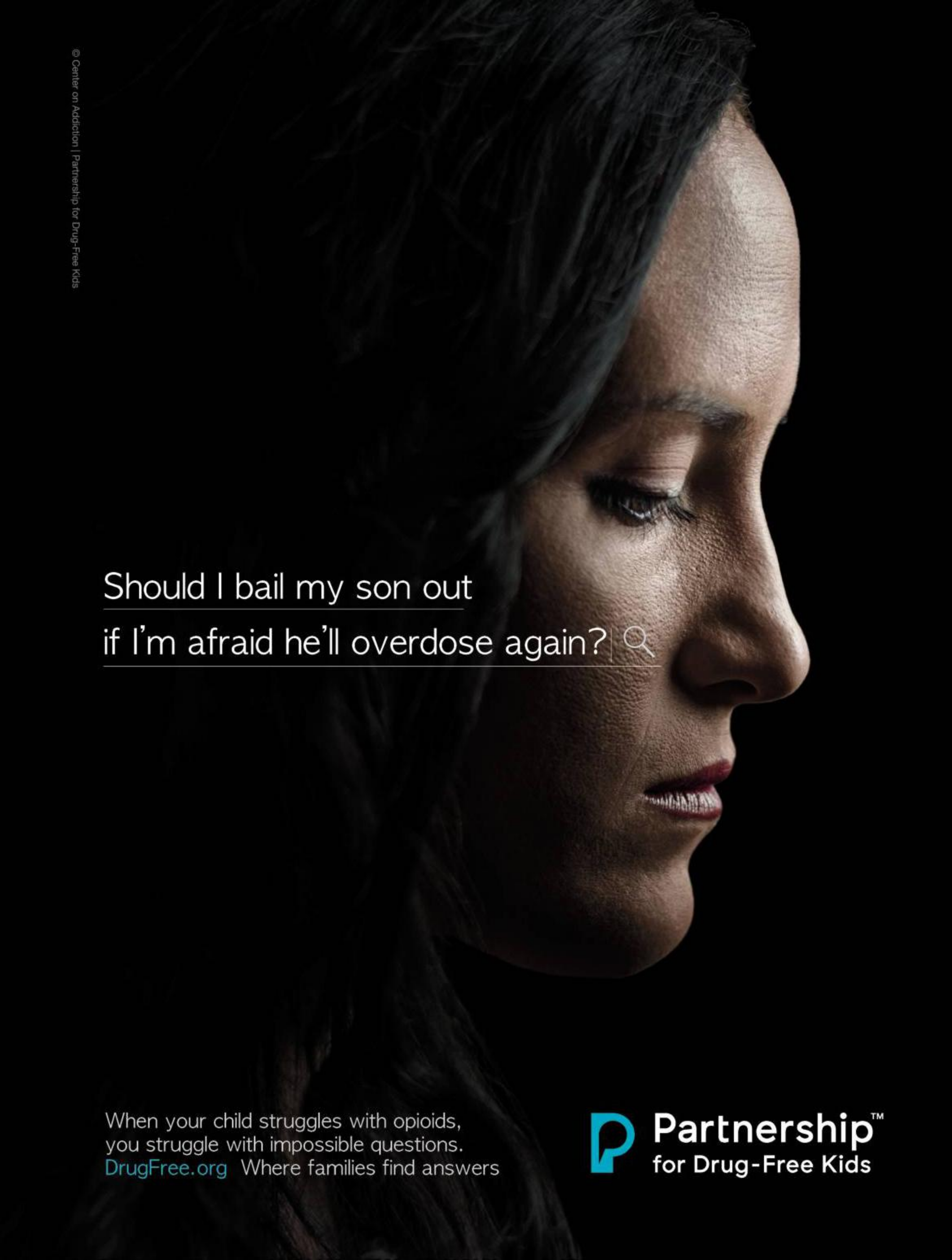
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Z Paige Lerario is a board-certified neurologist and transgender activist. They are currently a graduate student of social service at Fordham University and vice chair of the LGBTQI Section of the American Academy of Neurology. Their blog can be followed at https://blogs.neurology.org/author/mackenzie-p-lerario

Voice Training for Transgender People

Speech therapy and language strategies can help save lives

By Z Paige Lerario

Calling customer service is a situation we all know and dread. We navigate a maze of automated voice commands, hoping to speak with a real live person. For some that live connection is a relief—but not for everyone.

Within seconds the customer service agent uses cues from someone's voice—pitch, for instance—to decide to describe the caller as "sir" or "ma'am." For many who are transgender, that language is distressing when they are identified by the wrong gender pronoun or title. When we do not affirm a transgender person's identity, that person's risk for anxiety, depression and suicide can increase.

I am an openly transgender neurologist and activist. My research and that of others in this field point to two key ways we can support transgender people whose voice and gender identity do not align. First, small changes in language can help cisgender people (those whose gender aligns to traditional male and female categories assigned at birth) be more sensitive and accurate in the words they use. Second, gender-affirming voice treatments can be effective medical care, giving transgender people a valuable tool to express their identity to the outside world.

Many people perceive specific vocal traits as either masculine or feminine. For example, high pitch and vocal resonance from the face and mouth are often linked to a feminine identity. Low pitch and resonance from the throat and chest seem masculine. And different brain areas appear to process the voices of masculine versus feminine speakers. When people are unsure about a speaker's gender—as when experimenters manipulate audio to produce ambiguous voices—listeners show distinct brain activity as well.

Often a person's perceptions of voice and gender reflect long-standing beliefs learned over many years through social and cultural upbringing. For example, because many have been taught that gender is only male or female, their ability to describe voices that are more gender-ambiguous is limited. Nonbinary individuals are more likely to correctly identify speakers with such voices.

But this history, and the associations in the brain, does not mean these judgments are unchangeable. Learned behaviors can be unlearned or relearned. For example, my colleagues and I published a study looking at how language influences gender perception when hearing someone's voice for the first time. We recorded 24 transgender and cisgender people repeating a range of short words. Then 105 people of diverse genders from across the U.S. listened to these recordings and rated the gender of the speaker along one of several different scales. We found that the terms used in each scale could influence how listeners rated the gender of a speaker's voice. A scale that included binary "male" and "female" options led to more extreme results, rating speakers at one end or the other. But more graded "masculine" versus "feminine" scales led to rankings closer to the center, which allowed for individuals with an ambiguous or intermediate gender to be better represented. So a relatively small change in language could help reduce the odds of misgendering others.

More directly, voice therapies, both nonsurgical and surgical, can help a transgender person change their vocal characteristics, aligning them with their gender identity. Voice training is less costly and invasive than a throat operation, making it a more common starting point. Through sessions with a licensed speech-language pathologist, transgender people learn to control pitch, resonance, word choice and other vocal behaviors. Studies have found that most transgender people who undergo this training are satisfied with their results. Such training can improve quality of life, reduce voice-related disability and boost self-confidence.

Despite its benefits, many public and private health-care insurers in the U.S. do not cover voice training for transgender people. With several U.S. states now trying to ban gender-affirming health care for transgender adolescents, the situation will likely get worse. Many in the transgender community pursue self-training, without professional supervision. This increases their risk of learning unhealthy speech patterns that can damage vocal tissue.

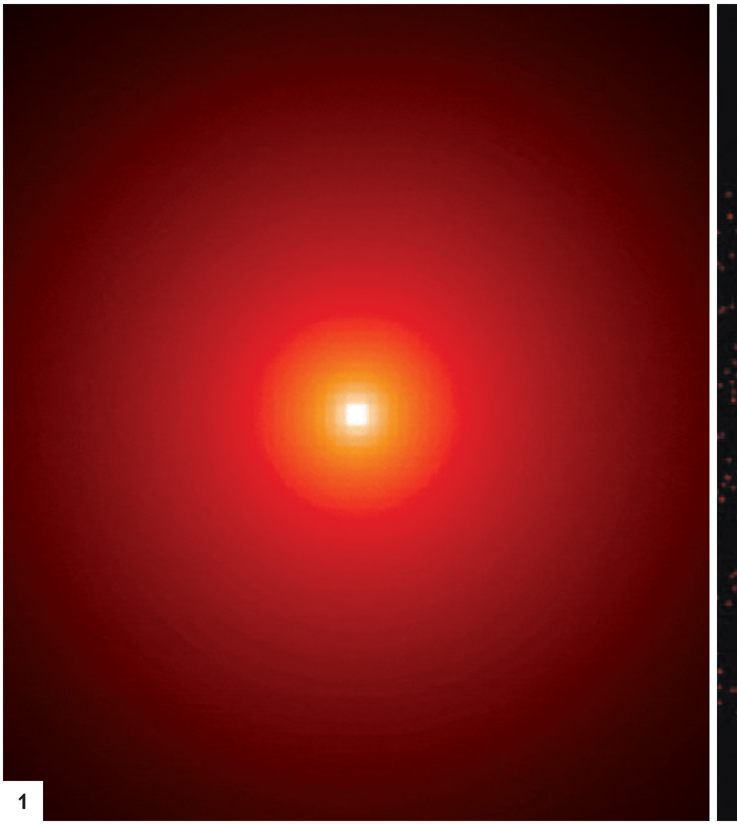
We should recognize voice training and gender-affirming surgeries as medical necessities, which should be covered by insurance. Like puberty blockers and gender-affirming hormones, these interventions save lives.

Illustration by Ada Buchholc

A Flash in the Night

The death of a massive star across the universe affected lightning on Earth

By Phil Plait



A blast of light called GRB 221009A, detected in October 2022, was initially so bright it outshone our own galaxy. The glow was observed in gamma rays by the Fermi Gamma-ray Space Telescope (*1*). Images taken just an hour after the first flare by the Neil Gehrels Swift Observatory show rings of x-ray light scattered by dust inside our Milky Way galaxy (*2*). The afterglow from the burst was seen in infrared light (*3*) five days after the initial blast by the huge Gemini South telescope in Chile.

NASA/DOE/Fermi LAT Collaboration (*1*)

In early October 2022 a wave of high-energy radiation swept over Earth from a gamma-ray burst, one of the most singularly catastrophic and violent events the cosmos has to offer. Astronomers quickly determined its distance and found it was the closest such burst ever seen: a mere two billion light-years from Earth. Or, if you prefer, 20 billion trillion kilometers away from us, a decent fraction of the size of the observable universe.

To astronomers, “close” means something different. This one was so close, cosmically speaking, that it was detected by a fleet of observatories both on and above Earth, and it is already yielding a trove of scientific treasure. But even from this immense distance in human terms, it was the brightest such event ever seen in x-rays and gamma rays, bright enough for people to spot its visible-light emission in smaller amateur telescopes, and was even able to physically affect our upper atmosphere. Despite that, this gamma-ray burst poses no danger to us. Either way, I’m glad they keep their distance.

Gamma-ray bursts, or GRBs, are intense blasts of gamma rays—the highest-energy form of light—that typically last from a fraction of a second to a few minutes in length. Gamma-ray bursts have been a puzzle to astronomers since the cold war, when the first one was discovered in the 1960s by orbiting detectors looking for nuclear weapons tested on or above Earth. More than 1,700 have been observed since then. Still, it took decades to pin any of them down well enough in the sky to observe them with more conventional telescopes and to understand better what they were. Even then it was difficult, as each GRB has idiosyncrasies, making them complicated to understand as a group.

Nevertheless, we do have a decent grasp of their basic nature. Short-duration bursts—generally a few seconds long at most—come from two superdense neutron stars colliding and blasting out fierce energy, whereas long-duration ones—lasting several minutes—come from massive stars exploding at the ends of their lives. The core of the star collapses, forming a black hole. A swirling disk of material that wasn’t immediately swallowed by the black hole rapidly forms around it, funneling twin beams of intense energy out into space, one pointing up and the other down, away from the disk. These eat their way through the dying star and erupt outward while the rest of the star explodes as a very powerful supernova.

The energy in gamma-ray bursts is almost incomprehensible: In a few seconds they can emit as much energy as the sun will over its entire 12-billion-year life span. Their power comes from their tight focus; these thin beams concentrate the explosive energy in a very narrow direction. If the beam happens to be pointed your way, you see a flash of gamma rays bright enough to be detected even from many billions of light-years distant. Outside the path you see a more typical supernova.

Despite their power, most bursts are at such a vast distance from us that their light is dimmed dramatically, and a telescope is needed to see them at all.

Dubbed GRB 221009A—for the first gamma-ray burst seen on October 9—its initial flash was first detected by sensors on the orbiting Fermi Gamma-ray Space Telescope, designed specifically to detect and rapidly find the locations of GRBs. Even for a long-duration burst, it was unusually extended. Another blast of gamma rays was spotted by the Neil Gehrels Swift Observatory, another orbiting set of telescopes designed to observe bursts. That second peak happened nearly an hour later, much later than usual for such events, indicating

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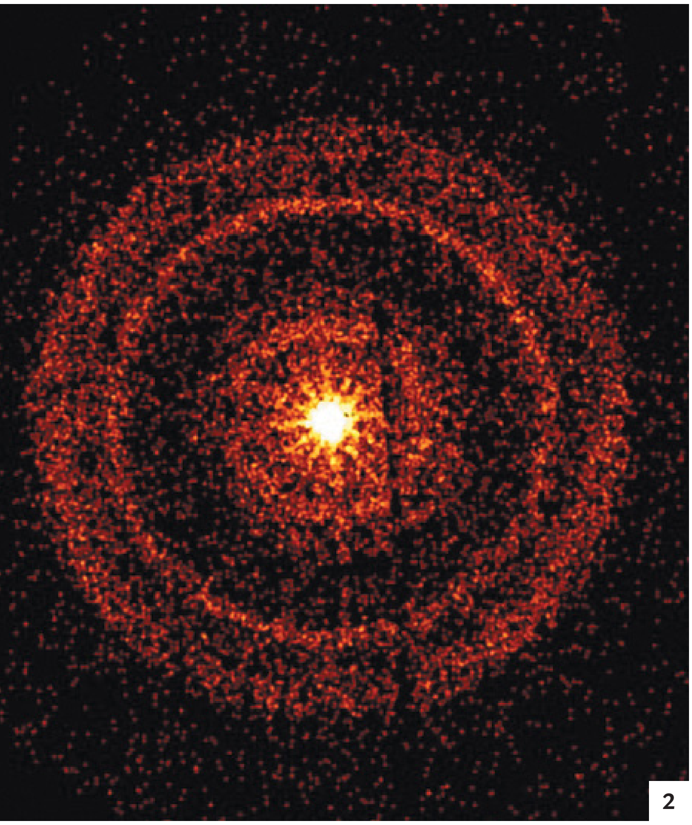

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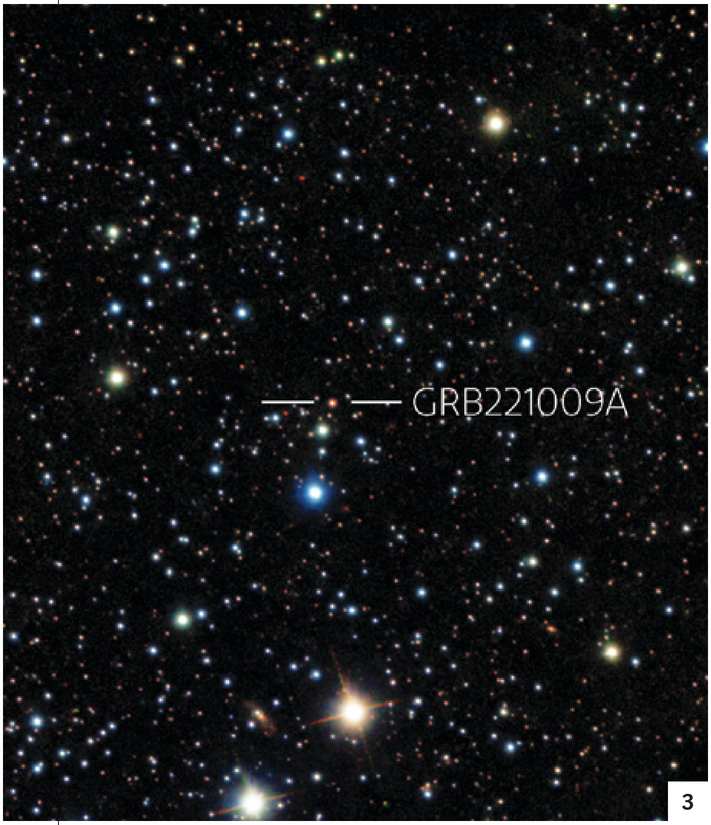

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NASA/Swift/A. Beardmore (University of Leicester) (2); International Gemini Observatory/NOIRLab/NSF/AURA/B. O'Connor (UMD/GWU) and J. Rastinejad and W. Fong (Northwestern University); Image processing: T. A. Rector (University of Alaska Anchorage/NSF's NOIRLab), J. Miller, M. Zamani and D. de Martin (NSF's NOIRLab) (CC BY 4.0) (3)

just how much power this particular GRB had at its disposal.

Swift immediately sent out an automated alert to astronomers all over the world, who responded by pointing their own telescopes toward the burst. The fading glow of visible light, caused by the beams slamming into matter surrounding the dying star, revealed its distance via cosmic redshift (a reddening of light caused by the expansion of the universe itself) and indicated this was the closest GRB ever seen.

A tweet by astrophysicist Rami Mandow pointed out that lightning detectors in India and Germany showed that the way pulses of electromagnetic radiation from lightning propagated changed suddenly at the same time the GRB energy hit our planet. These pulses indicate conditions in Earth's upper atmosphere changed, with electrons suddenly stripped from their host atoms. Gamma rays ionize atoms in this way, so it seems very likely that this blast physically affected our planet's atmosphere, though only mildly and briefly. Still, from two billion light-years away, that's an extraordinary phenomenon.

A GRB this close means that astronomers can analyze the light they see from it in more ways than usual. Typically a burst's light isn't bright enough to clearly reveal details about the event that caused it. This specimen could help scientists better understand the central black hole engine that forms during a burst and the extraordinarily complex nature of the physics surrounding it.

It can also tell us about the Milky Way. The Swift observatory saw expanding rings of x-ray light centered on the GRB's location, caused by dust clouds in the Milky Way located roughly 600 to 12,000 light-years from Earth. These "light echoes" happen when light hits dust clouds just off our line of sight to the GRB—so we see them to the side, next to the bright point in the sky. Because of the short amount of extra time it takes light from the blast to reach those dust clouds and be scattered toward us, we see rings of light moving outward from the center, their expansion rate related to their distance from us. Measuring these rings allowed astronomers to determine the distances to the clouds.

Although great strides have been made, especially since the 1990s when the first bursts were seen by optical telescopes and their distances were determined to be literally cosmic, there is much about them we have yet to understand. GRB 221009A is still being observed by telescopes around the world, and it may prove to be a Rosetta stone for these wildly diverse, bizarre and powerful events. SA

Editor's Note: This is the first of a new monthly column by astronomer and writer Phil Plait. Plait is a former Hubble Space Telescope researcher and has written numerous books and articles about space, including for ScientificAmerican.com.

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How Google is supporting the circular economy

For the vast majority of Earth's existence, our planet functioned as the quintessential circular system. The Sun's energy nourished trees into life, and once they fell, microorganisms broke them down into soil and nutrients, fuelling the next generation of growth. The notion of 'waste' did not exist — everything had a use.

It is only in the past few hundred years that humans have interrupted this cycle. With the rise of the Industrial Age came a linear economy built around the consumption of natural resources. Energy was turned into goods and products that we used — and then threw away.

This sliver of Earth's history improved the lives of billions of people, but it came at a tremendous cost to the planet's future. At our current pace, humanity needs 1.75 Earths to sustain our consumption of natural resources. We have been running a resource deficit since the 1970s that accelerates every year according to the Global Footprint Network, and by 2050, humanity will generate 3.5 Gt of solid waste annually[1].

To protect our planet while continuing to improve lives, we need to decouple economic growth from the consumption and disposal of finite resources. That is the core premise of the circular economy, which aims to minimize waste and maximize reuse of existing materials.

The circular economy also offers a critical pathway to mitigate climate change, because recycled and reused resources have lower carbon footprints. For example, improving the circulation and reuse of uncontaminated steel would avoid 500 Mt of new steel production by 2050, saving more than 1 billion tonnes of carbon emissions per year[2].

Figure 1. Zero-waste data centres. Google uses several circularity strategies at its globally owned and operated data centres, such as repairing components whenever possible to extend the life of servers.

Fortunately, the opportunity is as vast as the need. By making the most of our finite resources, we can not only thrive within planetary boundaries, but we can also generate an estimated US$4.5 trillion[3] in new economic output by 2030 and support efforts to achieve net-zero carbon emissions across the economy.

Google is committed to accelerating the transition to a circular economy in which business creates environmental, economic and community value through the maximum reuse of finite resources. To help inspire others toward a similar goal, we are sharing some of the lessons we have learned from our circularity programme — and the challenges that remain.

OUR THREE CIRCULARITY PRINCIPLES

Since our founding, Google has made it a core value to operate our business in an environmentally sustainable way. In 2007, we became the first major company to be carbon neutral for our operations. As of 2022, our sustainability programme takes a comprehensive view across carbon, water, ecology and circularity. We aim to achieve net-zero emissions across all of our operations and value chain — including our consumer hardware products — by 2030, to replenish 120% of the water we consume by the same year, and to become a circular Google within this more sustainable world.

Our approach to circularity is anchored around three core principles:

1. *Design-out waste and pollution.* This means designing for circularity from the start, enabling existing products to become future resources.
2. *Keep products and materials in use.* This means extending the effective life of products or materials as long as is safely possible, to make the most of all the resources that went into their creation.
3. *Promote safe and healthy materials.* This means designing products with materials that are safe for both people and the planet, recognizing that these materials will be used and reused long into the future.

These foundations are embedded into all aspects of our business operations, from the data centres we operate to the campuses we build, the products we create, the suppliers we work with, and the culture we encourage. The following section describes some of the progress we have made in each of these areas.

ZERO-WASTE DATA CENTRES

Google owns and operates 23 global data centres filled with servers and other equipment that provide reliable service to the billions of people who use our products every day. Our circularity goal for these centres is to achieve 'zero waste', defined as minimizing waste generation and maximizing the reuse of products and materials as much as possible while diverting 90% or more of solid waste from landfills.

As of 2022, seven of our 23 data centres have met this zero waste to landfill target and we are continuously making investments to advance waste diversion and recycling across our operations (**Fig. 1**). Additionally, since 2015, 32.6 million hardware components have been resold into the secondary market, and in 2021, 27% of upgrade components were from refurbished inventory[4,5].

Our approach to data-centre circularity starts with identifying the life-cycle stage of data-centre components. From there we apply several circularity strategies:

- *Maintain*. Whenever possible, we repair components to extend the life of servers.
- *Refurbish*. When a server or equipment is decommissioned, we create an inventory of usable, refurbished components that are stored for future reuse.
- *Reuse*. Any excess components are resold on the secondary market, following a rigorous security process.
- *Recycle*. Components that cannot be reused or resold are sent to an electronics waste-recycling partner.

Proof point: European data centre in Denmark. One of our newest European data centres, located in the Danish town of Fredericia, achieved zero-waste to landfill from day one — and continues to make important progress. Site management is working with a waste partner to recycle additional material that is otherwise sent to waste-to-energy recovery. This has required close partnership with staff and our vendors to find innovative solutions for waste collection and separation.

CIRCULAR CAMPUSES

Google has offices in over 180 cities spanning nearly 60 countries. We take a holistic approach to circularity in our offices and campuses, which starts by designing buildings with healthy materials and continues with reducing food and plastic waste in our workspaces. Our three key areas of office circularity are:

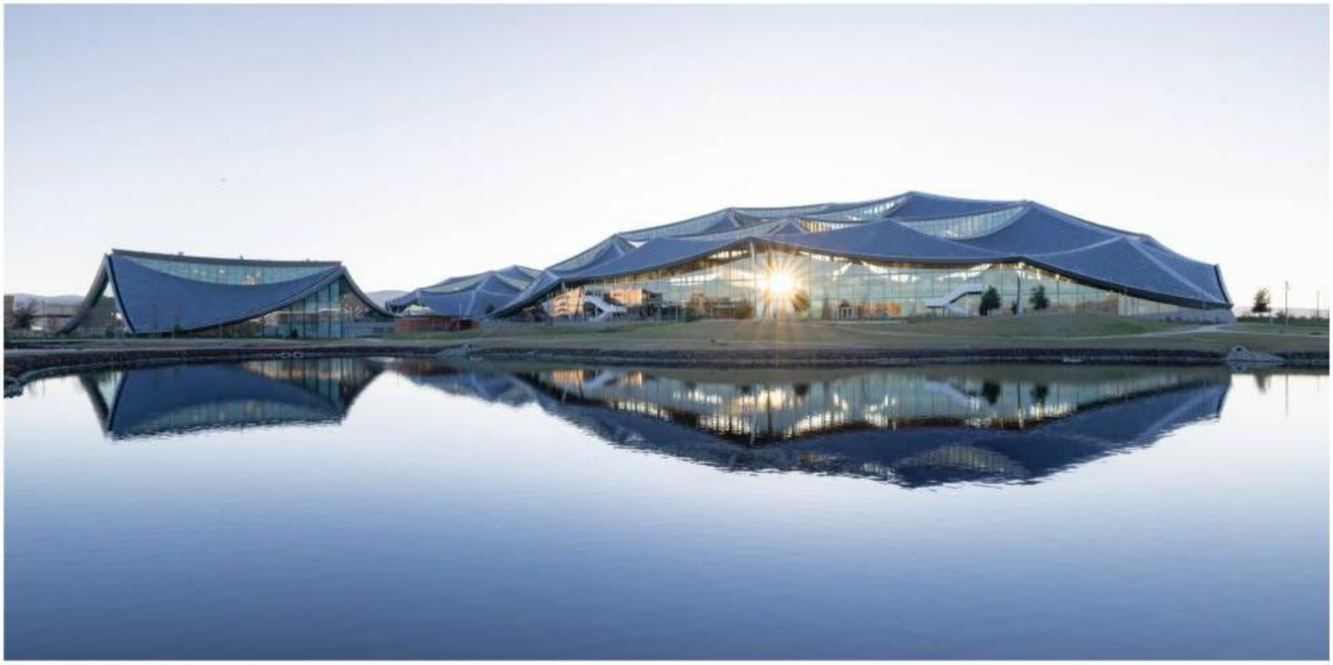
- *Food waste*. Our food programme aims to reduce waste through composting, donation and tracking use to right-size orders. We recently announced a goal of sending zero food waste to landfills — and cutting food waste in half for each Google employee — by 2025. We also use behavioural nudges that encourage Googlers to take only the food they will eat. For example, by reducing the depth of our cafeteria bowls by an inch, we found that Googlers took smaller portion sizes, which reduced leftover plate waste by 30–50% (ref. 6).
- *Plastics waste*. We work to reduce single-use plastics and other plastic waste through a series of interventions, including procurement, operational changes and workspace design. These efforts include eliminating the purchase of single-use plastics wherever possible and making reusable drinking options (like our sustainable hydration stations) easy to use in our micro-kitchens.
- *Building and construction materials*. In developing our office spaces, we promote circularity through a number of practices, including procuring salvaged and reused materials in construction projects, designing our facilities to enable zero-waste operations, and setting ambitious waste-diversion targets to keep material out of landfills. For example, since 2012, we have had a robust salvage programme, working with non-profits to find new homes for usable building components such as doors, plumbing fixtures and tiles.

Proof point: Bay View and Charleston East campuses. Our new Bay View and Charleston East campuses mark significant steps forward for our circularity programme (**Fig. 2**). At both locations, we vetted thousands of building materials against the Living Building Challenge (LBC) Red List to eliminate 'worst in class' materials and chemicals with the goal of creating a safer, more circular environment. Both campuses incorporated salvaged materials into the building design, and both aim to reduce future renovation waste through highly flexible and reconfigurable work areas. At Charleston East, in particular, more than 22,000 imperial tons of construction waste had been diverted as of October 2021, and 530,000 pounds of drywall waste was recycled as part of a closed-loop wallboard initiative. With these efforts, Charleston East is set to be one of the largest projects ever to attain an LBC Materials Petal certification for healthy building materials.

PRODUCT AND HARDWARE DESIGN

Millions of people use Google products like Pixel, Nest, Home and Fitbit every day, making these products a circularity priority area. Our product circularity approach involves several strategies:

- *Using recycled materials*. We are committed to using recycled or renewable content in at least 50% of plastic across the product portfolio by 2025, prioritizing recycled plastic wherever possible. For example, the Nest Audio enclosure — which is composed of fabric, housing, a foot and a few smaller parts — is made from 70% post-consumer recycled (PCR) plastic. Our materials scientists and design engineers developed a custom PCR plastic in partnership with our suppliers, and we work closely with them to expand the market for recycled materials, including those we develop specifically for our products.
- *Practicing circular design*. We focus on material reuse and extending the useful life of our products as part of the fundamental design process. For example, we have a goal of making all packaging plastic-free and 100% recyclable by 2025. We also provide a number of repair options, such as making a full range of spare parts for Pixel 2 through Pixel 6 Pro products, including batteries, replacement displays and cameras, and we will provide at least five years of security updates for the Pixel 6 and Pixel 6 Pro, as well as future Pixel phones, from the date we start selling them on the US Google Store. Additionally, for Google Nest, we issue critical bug fixes and patches for at least five years after launch.
- *Eliminating waste*. We are committed to achieving Underwriters Laboratory (UL) 2799 Zero Waste to Landfill certification at all final assembly manufacturing sites by 2022. We are also reducing



Iwan Baan for Google

Figure 2. Circularity at Bay View and Charleston East. These new Google campuses feature many circularity strategies, such as incorporating salvaged materials to promote reuse and designing flexible spaces to reduce renovation waste.

packaging waste from our suppliers when they ship parts to our manufacturing sites. Additionally, for consumers, we are developing tools and programmes to help people properly recycle electronic goods. For example, we recently made it easier for people to find out where they can recycle or dispose of electronic goods using Google Maps and Search. And we continue to research and pilot new ways for customers to recycle e-waste, including through a doorstep-recycling pilot programme in Denver, Colorado.

- *Promoting safer chemistry.* We strive to select materials to use in our products that have a chemical composition that is safe for both people and the planet — both now and far into the future. For example, we make our restricted substances specification publicly available while also aiming to use safer flame retardants and eliminate antimicrobials across all of our products by 2023.

Proof point: recycled aluminium. As part of our work toward a more circular Google, we developed a 100% recycled aluminium alloy to meet our Google Pixel performance standards, validated by a third-party certifier (**Fig. 3**). The Pixel 5 was our first phone to incorporate this recycled aluminium, which not only eliminates the use of mined aluminium in the enclosure and reduces waste but also lowers the carbon footprint of manufacturing the enclosure by 35% (based on a third-party-verified life-cycle assessment) compared to using virgin aluminium. At the time of writing, the aluminium inside the back housing of the Pixel 5, 6 and 6 Pro is made with 100% recycled content. We also want other companies to benefit from our work and for other manufacturers to use this alloy in their products. That is why we require our suppliers to make this alloy available to manufacturers across the electronics industry.

For more information about our sustainability claims, please visit https://store.google.com/magazine/sustainability.

ENABLING EVERYONE

Even as we work to build a more circular Google, we recognize that realizing a circular economy will take everyone's participation. To support broader adoption of core circularity practices, we are building tools and partnerships that enable and empower others to reduce waste and reuse materials. A few notable efforts are as follows:

- *Enabling better recycling.* We have now made it easier for people to find out where they can recycle electronics, batteries, glass bottles, clothing and other goods using Google Maps and Search. Local merchants and shops can show the recycling services they offer, and more people can find these options just by searching something like "battery recycling near me" (**Fig. 4**). People can also suggest edits to the available recycling options at a location, helping others in their community find the right place for them.
- *Helping officials cut plastic pollution.* Every year, rivers carry millions of tonnes of plastic into oceans. We partnered with the United Nations Environment Programme (UNEP) to develop a new machine-learning model that shows a highly accurate view of plastic pollution, with a launch demo focused on the Mekong River in Thailand. This open-source model empowers local government to take action and scale new solutions.
- *Facilitating household circularity.* We have empowered people to take action on circularity in their everyday lives with our interactive tool, Your Plan, Your Planet. The tool features lessons on extending the life of household goods, along with a teachers' companion guide for schools. It also includes tips around water conservation, energy savings and more.

CIRCULARITY'S ROLE IN CLIMATE CHANGE

While the circular economy is critical from a global resource

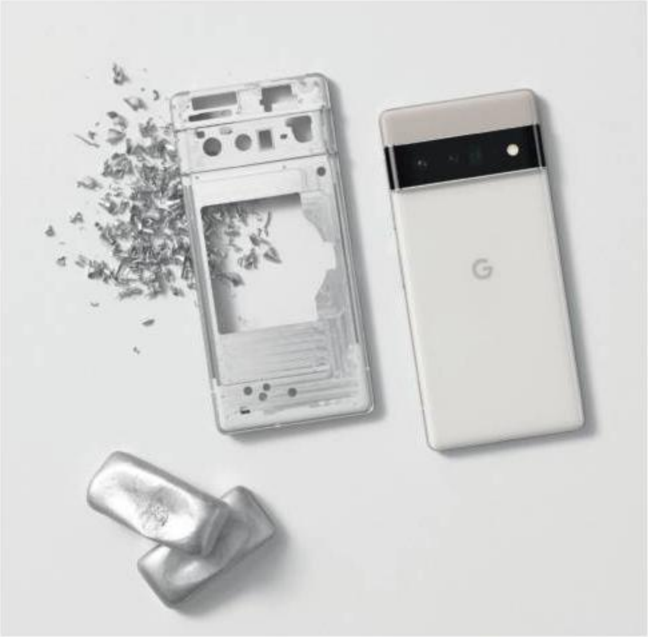


Figure 3. Recycled aluminium in hardware. Google developed a 100% recycled aluminium alloy, validated by a third-party certifier, to improve circularity in the Pixel phone.

perspective, it is also essential to addressing climate change. Simply put, the world cannot achieve a net-zero carbon-emissions target without the circular economy.

Global greenhouse gas emissions are expected to reach 51 Gt by 2050 (ref. 7). About 45% of that comes from 'embodied' emissions, or carbon generated from the production of new buildings, cars, clothing, food and other common goods or products. The circular economy has a key role in stopping the disposal of embodied carbon en route to a net-zero world. Every piece of waste represents a new product that will be created from scratch — and thus a missed opportunity to cut embodied emissions.

We can seize that opportunity and cut up to 10 Gt of carbon by 2050 (ref. 7) through several circular strategies described in greater detail elsewhere in this article, including:

- *Deconstruction.* Make better use of buildings through practices like deconstruction and reuse, low-carbon construction materials such as mass timber, and retrofitting or repurposing existing spaces.
- *Circular design.* Reduce the need for new products and materials by supporting longer product lifecycles, reuse programmes and recycling.
- *Recycled materials.* Use recycled materials to create new goods and products, as recycled resources generate significantly lower greenhouse-gas emissions than virgin resources during production.

EMERGING OPPORTUNITIES

As we build on our progress in the years to come, we see a number of exciting areas with the potential to further accelerate the transition to a circular economy.

Artificial intelligence

Artificial intelligence (AI) is becoming a tool to help address challenges facing many industries, and waste is no exception. Recent estimates suggest that AI's ability to design-out food waste can create US$127 billion in annual value by 2030, and its ability to improve consumer electronics is valued at US$90 billion a year[8]. Our 2019 white paper identified three primary ways that AI can support circularity:

1. *Design circular products, components and materials.* For example, AI can generate insights that help significantly shorten the design timeline of microchips, which reduces the total amount of materials needed for research and development.
2. *Operate circular business models.* For example, our food team, in collaboration with X, Alphabet's moonshot factory, is using AI to speed up the food-inspection process, strengthening the supply chain and reducing waste.
3. *Optimize circular infrastructure.* For example, AI-powered computer vision can help industrial robots classify waste on assembly lines with very high accuracy, leading to better sorting at recycling facilities.

Deconstruction and reuse

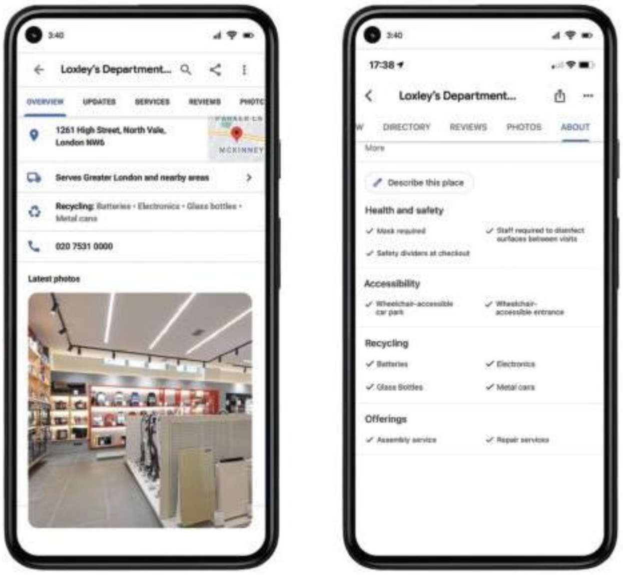
Roughly 11% (ref. 9) of global emissions come from construction and the creation of new building materials — an impact that is locked-in forever and cannot be reduced through technological improvements. Commercial deconstruction and reuse practices can help address this impact by promoting the use of low-carbon materials and encouraging adaptation of commercial buildings. Our 2019 white paper identified the following areas of opportunity for deconstruction and reuse in office development:

- *Design and build for circularity.* Development projects can prioritize healthy materials (including mass timber where feasible), design adaptable spaces that can change without needing extensive renovations, design for disassembly to avoid demolition waste, and create a deconstruction plan from the start. Regulation has an important role to play in supporting these practices.
- *Set-up salvage for success.* Cities can support salvage practices by requiring salvage plans during the building permitting phase and otherwise incentivizing the practice. Buildings can develop salvage inventories from the start that can make it easier to reuse or save equipment and materials throughout the life of the space.
- *Scale and diversify the deconstruction workforce.* Local jurisdictions can require 'salvage-ready' contractors for commercial projects and should support workforce training in deconstruction as a specific growth skill.
- *Strengthen the regional reuse marketplace.* There are a number of ways to strengthen the reuse market and support the circular economy of commercial buildings, including setting salvage targets, embracing virtual salvage marketplaces, and requiring salvage during public project procurement.

Electronic waste

Electronic waste (e-waste) is one of the world's fastest growing waste streams. In 2019, only 17% of e-waste was recycled globally, according to Statistica. The rest often ends up in landfills, is improperly disposed of in the environment, or 'hibernates' — the practice of keeping a product that is no longer in active or regular use — in our homes. This practice limits the ability to recycle usable materials and e-waste, meaning that more new resources must be consumed to create new products.

In 2021, we conducted an assessment of why consumers engage in product hibernation instead of recycling and identified the following areas of opportunity[10] (it should be noted that there are usually multiple factors in a decision to hibernate a product, and that the key factors differ by product, so pursuing all of these areas is critical to maximize electronic recycling):



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- ✓ Electronics
- ✓ Glass Bottles
- ✓ Metal cans

Offerings
- ✓ Assembly service
- ✓ Repair services

Figure 4. Search 'battery recycling near me'. Google Maps and Search now make it easier for people to find places near them that recycle a variety of goods, such as batteries, eletronics and glass.

- *Low handoff-option awareness or convenience.* Consumers may lack information about proper recycling methods or facilities or find that option inconvenient. Google is working to address this problem through Maps and Search programmes (described earlier) that help identify and access local e-waste recycling options.
- *Compensation expectations (financial or social).* Consumers often expect compensation for their e-waste, although this exchange can be social in nature, taking the form of product donations.
- *Keeping spare products.* Consumers often keep old products in case they need to replace a broken one. Stronger repair programmes can help, such as our programme for the Google Pixel described earlier.
- *Data retrieval and removal.* Consumers often hold on to products because they lack easy or reliable ways to transfer or erase data from the devices.
- *Device nostalgia.* Consumers often feel an emotional attachment to their devices, which causes reluctance to part with them.

CHALLENGES AHEAD

We are excited by the progress made by Google's circularity programme to date, as well as by the opportunities on the horizon. We also recognize the many systemic challenges hindering even greater progress — some of which we identify below. Overcoming these and other barriers will be critical to realizing the circular economy as soon as possible.

Improving data availability

The circular economy aims to make the most of every resource we use. To do that requires high-quality, standardized data enabling the market to identify, manage and value all the resources available at any given time. For example, rather than seeing a piece of plastic as an item to use and discard, we should see it as bits of information that tell us how it can be reused, what it is worth in terms of recycling, and where it is needed. Such data should inform capital investments, infrastructure priorities, business plans, policy interventions and more — as such, we view data availability as a key to accelerating the transition toward the circular economy. This challenge is one we feel particularly inspired to help solve as a data company, working alongside others.

Scaling innovation

The circular economy is in a similar place to where renewable energy was a few decades ago: we knew where we needed to go but often lacked the right technologies to help companies, governments and households get there in a cost-competitive way. Innovation helped bridge that gap, with the rise of advances such as new silicon systems to capture sunlight, larger wind turbines to capture energy and longer-lasting batteries to power electric vehicles. We need similar innovation around the way products and materials are designed, manufactured, used, reused, or recycled back into the economy. We need accelerators, venture funding and other forms of support focused on turning great circularity ideas into leading technologies. We plan to leverage Google's ingenuity, technical leadership, cultural influence and talented people to help do just that.

Embracing the future

Meeting this moment demands a spirit of exploration and discovery. In nature's circular system, it is the novel adaptations that pave a new path. Similarly, we need innovative thinkers to inspire a shared sense of purpose around this new direction and rally collective action. For our part, we can help by connecting billions of people every day and sharing our own lessons and experiences.

MOVING FORWARD TOGETHER

The circular economy, by definition, connects everyone. It is in that spirit of cooperation that we describe the approach Google is currently taking, recognizing that we do not have all the solutions and that true progress will span the global economy. We need business leaders to partner across industries and reduce costs, governments to incentivize action and protect the public good, innovators to keep looking ahead and thinking big, and people everywhere to know that no action is too small.

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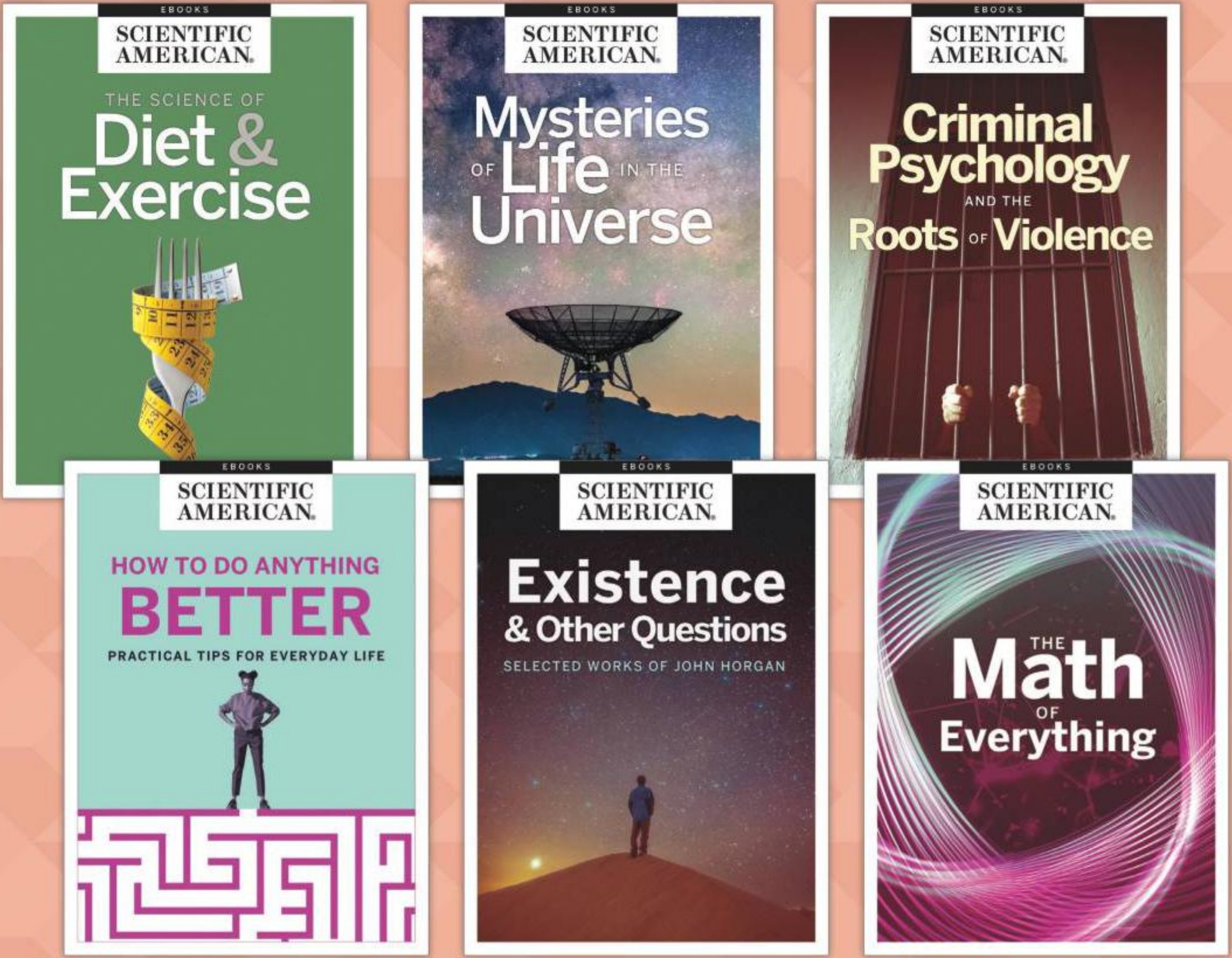
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REVIEWS

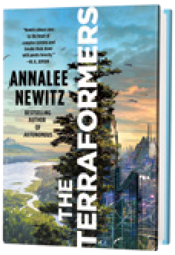
Edited by Amy Brady

FICTION

Future Imperfect

What kind of world would humanity build with another chance to do it right?

Review by Siobhan Adcock



The Terraformers
by Annalee Newitz.
Tor Books,
2023 ($28.99)

Great stories often start from a tantalizing "what if?"—the more irresistibly original the premise, the better. In *The Terraformers,* the new novel from i09 founder and former Gizmodo editor in chief Annalee Newitz, the central question points straight at our planet's existential crisis: Given the painful lessons we've learned about how *not* to build a sustainable, equitable future, what if people had a chance to create a cleaner, fairer Earth 2.0? Could we succeed?

It will surprise no one that the answer is a resounding "well, maybe." Newitz's formidable imagination can't change the fact that people are people. Yet the novel smartly argues that people—particularly when the term expands to include sentient forms far beyond humans—might just be a planet's best resource. Even if takes a millennium's worth of creativity to offset rapacious corporations, unethical developers, ineffective governments and standard-issue corruption.

The novel's first scene sends up a classic trope of science fiction, the "first contact," in which representatives from two civilizations meet on an alien world. Except in this case, the alien world is an early-stage planet called Sask-E, which has been modeled after the original Earth by a terraforming corporation known as Verdance, and the first encounter is between two very different versions of *Homo sapiens.* One is a resource-plundering, trash-talking, trash-generating, remotely operated proxy, and the other is Destry, an Environmental Rescue Team ranger who proceeds to show what happens when someone tries to mess with her boreal forest.

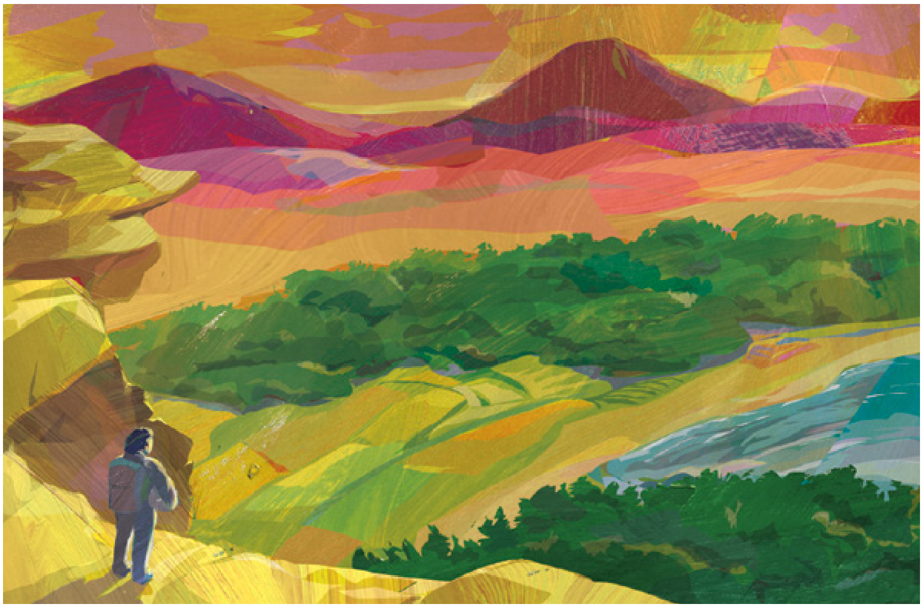
Sask-E appears at first to be an Eden of wild beauty and limitless potential. But as the good-hearted Destry discovers, the developers who created Sask-E—and who hold both her job and her life in their clutches—aren't out to make a better world. Their true goal, not shockingly, is profit. The discovery of an underground civilization on Sask-E forces Destry to choose sides in a conflict that alters her beloved planet's future.

From here the novel takes running leaps through time. Terraforming is a slow process after all, and readers who get invested in Destry's character might be saddened to learn that this isn't really her story. Newitz's plot skips across generations of people who come after Destry—an appealingly diverse cast of rangers, scientists, engineers and an utterly endearing autonomous collective of sentient flying trains. If the antagonists in Newitz's novel are thinly outlined, it is perhaps because the novel's big "what if?" demands some fairly broad strokes. Each character plays a part in answering whether well-intentioned people can save the best parts of Sask-E from the worst depredations of runaway consumer culture fostered by slimy corporate interests and lazy government.

As the story of Sask-E's rise, ruin and slow road to redemption unfolds over thousands of years, Newitz's attention is on the complex symbiotic relation between technologies and cultures, another classic trope of science fiction that they also explored in their 2021 nonfiction book, *Four Lost Cities: A Secret History of the Urban Age.* The same technological innovations that push a civilization to new heights of achievement can also be complicit in that civilization's undoing.

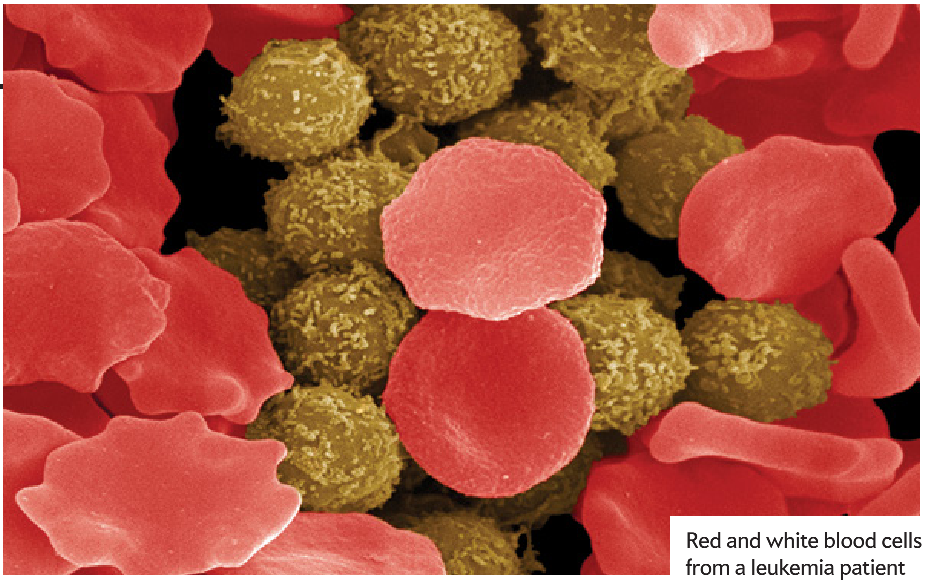
On Sask-E, however, technology has made possible an entirely new definition of personhood. Animals, robots, hybrids, and even doors and worms are in communication with the humans of the future. And thanks to a galactic accord known as the Great Bargain, they all have a valid seat at the negotiating table. Once the assumption that only humans are people is swept away, thorny questions of natural resource allocation, representative government, inclusive language and sexual freedom are up for reevaluation. (If you've ever wanted to know how a sentient train can couple with a robot or a cat, your answer is here. As one character remarks, "Where there's desire, there's data.")

As messy as all this sounds, it opens up thrilling new pathways of hope that Earth 2.0 might succeed. *The Terraformers,* refreshingly, is the opposite of the dystopian, we're-all-doomed chiller that's become so common in climate fiction. Newitz's mordant sense of humor steers the story clear of starry-eyed optimism, but it's easy to imagine future generations studying this novel as a primer for how to embrace solutions to the challenges we all face. If we're ever going to save ourselves from ourselves, then maybe what we need is a new way of thinking about *self.*



Siobhan Adcock is a writer and editor whose most recent novel is *The Completionist.*

Illustration by London Ladd



Red and white blood cells from a leukemia patient

Steve Gschmeissner/Science Photo Library/Getty Images

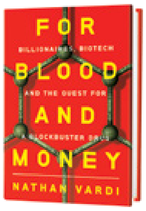
NONFICTION

Blood Money

A cinematic tour of ambition, greed and desperation in biotech

"Finding new therapies that target only cancer cells and did not kill healthy cells had become the holy grail of cancer drug development," writes Nathan Vardi, a managing editor at MarketWatch and former editor at *Forbes*. *For Blood and Money* follows the path of one class of such products ("targeted small-molecule drugs" designed to fight blood cancers) that ultimately pits two biotech companies against each other in a race to market—and to an unimaginable payday. Readers are introduced to scientologists, restless entrepreneurs, clinical experts and the machinations of magnate financiers searching for the next billion-dollar blockbuster. In the middle of that friction of ambition and greed are the patients, desperate for cures and more time.

The story begins with Pharmacyclics, a small biotech company in California that is working on a drug to treat leukemia. Along the way, we meet charismatic and sometimes capricious executives and investors, as well as revolving doors of employees being hired, fired and starting new companies (and competitors).



For Blood and Money: Billionaires, Biotech, and the Quest for a Blockbuster Drug
by Nathan Vardi.
W. W. Norton, 2023 ($30)

Vardi examines the fraught, infamously slow FDA market-approval process, but the pacing of the book remains quick. With the focus on characters shifting from chapter to chapter and a vast number of names—people, companies, drugs—included for detail, it can feel at times that one needs a color-coded organizational chart to keep up.

In the quest for magic-bullet biopharma drugs, a particularly disquieting element is how powerful investors become drivers of medical strategy. The scientific search for cures often seems overmatched by the outsized desire to be first and to reap the highest returns; one could be forgiven for wanting to rename the book *For Money and Blood*. The profits are astronomical, yet investors still consider how much they've left "on the table."

Still, there are meaningful collaborations, and many characters in the book genuinely want to do right for patients with deadly diseases. Readers remain distinctly aware of those who have benefited (and continue to benefit) from these drugs. Yet the banks, investors and hedge funds leading the search underscore an overall health-care system that feels skewed in its priorities.

Vardi, who is clearly knowledgeable about Wall Street and biopharma, depicts the nuances of both in a vivid, cinematic fashion. One can already imagine the movie version. —*Mandana Chaffa*

IN BRIEF

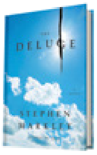
The Land Beneath the Ice: The Pioneering Years of Radar Exploration in Antarctica

by David J. Drewry.
Princeton University Press, 2023 ($39.95)

Glaciologist David J. Drewry takes readers to the frigid research outposts where he and his colleagues pioneered the technique of radio-echo sounding to plumb the depths of the Antarctic ice sheet. Drewry explains how this new technology emerged to compensate for inadequacies of past methods, then shares his own experiences mapping invisible mountain ranges and, worryingly, lakes deep under the ice that are hastening melt. A peppering of photographs and delightful personal anecdotes show the excitement and frustration that are inevitable during scientific expeditions. —*Fionna M. D. Samuels*

The Deluge

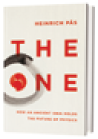
by Stephen Markley.
Simon & Schuster, 2023 ($27.99)



Stephen Markley's epic novel creates a full-scale panorama of a world bludgeoned by climate change, even as it magnifies the struggles of those caught in its vast and unrelenting chaos. Activist groups A Fierce Blue Fire and 6Degrees both attempt to provoke government and industry into addressing the climate crisis, but their divergent philosophies take them down different paths as society unravels. Markley's dark depiction of the near future is filled with vivid descriptions of climate catastrophes, but his intricate network of complex characters balances precision with pathos, offering a kaleidoscopic view of humanity's fraught relationship with its changing planet. —*Dana Dunham*

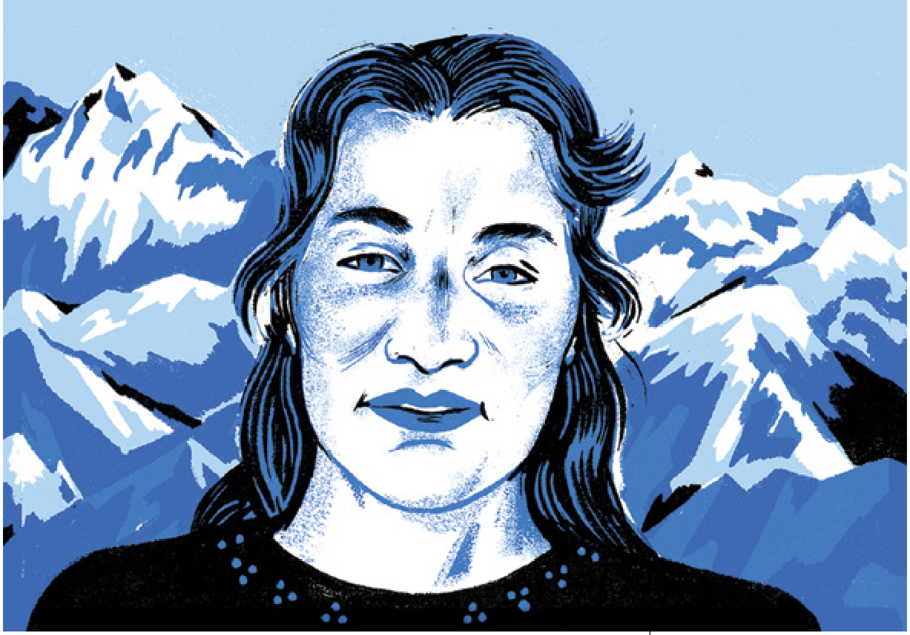
The One: How an Ancient Idea Holds the Future of Physics

by Heinrich Päs. Basic Books, 2023 ($32)



Which is more fundamental, the many or the one? Author Heinrich Päs believes physics gestures at an underlying unity simple enough to count on one finger. If only physics would embrace monism, its deepest mysteries would yield to that magic number. But monism was declared a heresy, first by the medieval Church and second, in Päs's telling, by physicist Niels Bohr. Even if the connections between ancient monism and modern science are a stretch and Bohr is reduced to caricature, the history is thoroughly researched, the physics is cutting edge and Päs's larger point resonates: much, or maybe all, of what we take for reality is an artifact of our limited perspectives. —*Amanda Gefter*

Naomi Oreskes is a professor of the history of science at Harvard University. She is author of *Why Trust Science?* (Princeton University Press, 2019) and co-author of *Discerning Experts* (University of Chicago, 2019).



The Inspiration of Hilaree Nelson

What great athletes and great scientists have in common

By Naomi Oreskes

A very sad piece of news in 2022 was the death of Hilaree Nelson at age 49. A premier ski mountaineer, Hilaree held numerous firsts, including the first ski descent from the summit of Lhotse (next door to Mount Everest), the first ski descent of Papsura in India (and known as the "peak of evil" because of its exceptional danger), and the first person to ski the Five Holy Peaks of Mongolia.

Hilaree helped to break the barrier of "women's firsts." When people spoke of her, they didn't say she was one of the world's great female mountaineers. They said she was one of the world's great mountaineers. In 2018 she succeeded Conrad Anker—who had climbed Everest three times, twice without oxygen—as captain of the North Face Global Athlete Team, cementing her position as one of the greatest adventurers ever.

Tragically, after reaching the summit of the world's eighth highest peak, Mount Manaslu in Nepal, with her life and ski partner Jim Morrison, Hilaree was caught in an avalanche and fell to her death.

I had met Hilaree through our mutual work with Protect Our Winters (POW), a nonprofit advocacy group that works to educate the outdoors community and industry about climate change and mobilize them into action. Founded by world-class snowboarder and businessperson Jeremy Jones, POW brings athletes, such as Hilaree, to speak with students, community groups, business leaders, the U.S. Congress, and others about the changes they are seeing around the globe. As Hilaree wrote, "Climate change is real. I know this because I've seen it with my own eyes."

In 2018 we appeared together at two events at the World Economic Forum in Davos, Switzerland. One was a panel discussion; the other featured Hilaree discussing her life's work and passion, including a startlingly honest discussion of her mistakes, including some very costly ones. She described a 2014 expedition that she led in an attempt at the first summit of Hkakabo Razi in Myanmar, where her team nearly ran out of food. Hilaree told us how the team "broke," how she had struggled to finish the expedition, and how the experience nearly broke her.

The World Economic Forum is populated by well-known, influential and eloquent people—our panel included former U.S. vice president Al Gore—but often audiences fidget. There's a lot to take in. When Hilaree spoke, however, her listeners were rapt. After the event, people swarmed her, eager to hear more, ask a question, or just to say hello. When we dined later, a 14-year-old girl came up to our table to ask Hilaree for her autograph.

I've thought a lot since then about what made Hilaree so inspiring and also about what makes great scientists inspiring. Great scientists may not put their lives at risk the way Hilaree did, but they also inspire awe, admiration and requests for autographs. Athletes and scientists share one thing: the ability to do things that other people simply can't do. In theory, this could make us feel small and insignificant, but that's not what I've observed. Rather we are reminded that things that may seem impossible might not be.

Both great athletes and great scientists are blessed with conspicuous talent, but they also work hard and push themselves in extraordinary ways. When we are around them, we can think—even if subconsciously—that maybe if we push ourselves, we can do more than we thought possible, too. Most of us will never climb Everest, much less ski it—and nor should we try—but we all have the capacity to do more than we have done before.

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Illustration by Irene Rinaldi

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Compiled by Mark Fischetti

JANUARY

1973 Hydrogen Power

"The basic dilemma represented by what has been termed the 'world energy crisis' can be simply stated: the earth's nonrenewable fossil-fuel reserves will inevitably be exhausted, and in any event the natural environment of the earth cannot readily assimilate the byproducts of fossil-fuel consumption at much higher rates without suffering unacceptable levels of pollution. Major energy-consumption categories as transportation, space heating and heavy industrial processes are primarily supplied with fossil-fuel energy. If the 'energy gap' of the future is to be filled with nuclear power in the form of electricity, then the U.S. will have gone a long way toward becoming an 'all-electric economy.' A case can be made for utilizing the nuclear energy indirectly to produce a synthetic secondary fuel that would be delivered more cheaply and would be easier to use than electricity in many large-scale applications: hydrogen gas."

Classified Universities

"Although the volume of secret Government research conducted in U.S. universities has declined sharply in the past decade, in part because of protests by students and faculties, a number of large institutions, chiefly state universities, continue to undertake classified projects. In fiscal year 1972 the Department of Defense has at least 29 classified contracts with universities, not counting contracts for work done at off-campus facilities. Of the contracts, 12 are with two institutions: the University of Texas and the University of Michigan."

1923 Cheerful Tax Givers

"At Thebes, the ancient capital of Upper Egypt, archaeologists from Pennsylvania University have found demotic, or common-language, papyri that fill a gap in history from B.C. 309 to 246. This period includes the reign of Ptolemy Philadelphus, who was so successful in levying heavy taxes with a minimum of injury and dissatisfaction. As the manuscripts deal mainly with financial affairs, our own Ptolemies may perhaps learn from them how to create in us a nation of cheerful givers."

Heating with Shale Oil

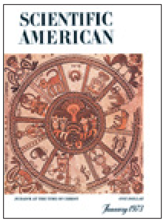
"From Sweden comes the report that peat briquettes, which have been impregnated with shale oil, make a very good substitute for coal. The process of impregnation consists merely in mixing the powdered peat with 10 percent by weight of shale oil and then briquetting. The price of such briquettes is stated to be one-half that of anthracite coal."

1873 Sewing Machine Monopoly

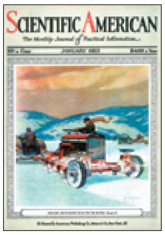
"The Sewing Machine Ring, composed of the Singer, Howe, Grover & Baker and Wheeler & Wilson Companies, failed to induce our last Congress to sanction their modest attempt to fasten their overgrown and unjust monopoly for another seven years. Consequently their efforts are to be redoubled, and whatever influence, political or pecuniary, that can be brought to bear will be unhesitatingly wielded during the coming spring in one last grand endeavor to force the job through the Forty-second Congress. The patent, which has already expired and on which a third term is asked, is for the 'feed' motion. The owners will, if the present measure be passed, again rule the entire sewing machine trade. Thousands of inventors, who have devised improvements of great practical value, are subject to the mercy of this Ring, which may drive them from the market and deprive the public of as good machines at cheaper rates."

Alcohol from Moss

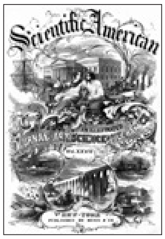
"In the northern governments of Russia, large quantities of alcohol are produced from the mosses and lichens growing there in enormous quantities. This new industry originated in Sweden, and was subsequently introduced in Finland. Several large distilleries exhibited such alcohol at the recent industrial exposition in Moscow, where German, French and English manufacturers praised its quality highly."



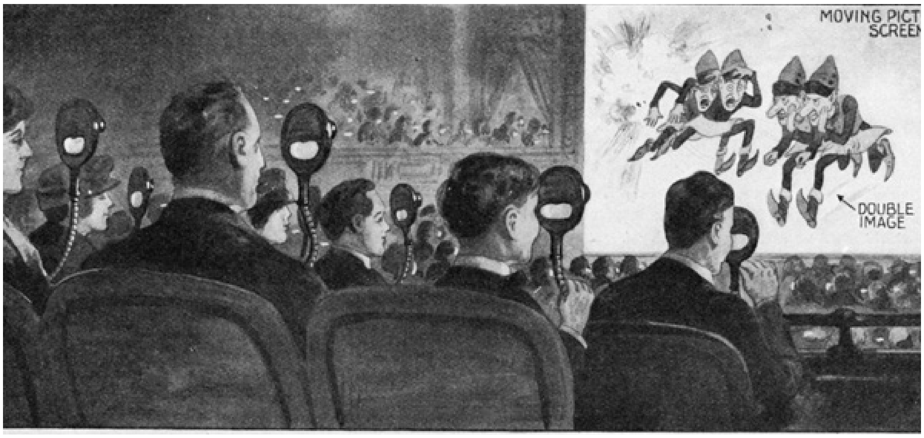
1973



1923



1873



1923, 3-D MOVIES: "Many attempts have been made to produce stereoscopic motion pictures that have a third dimension, depth. The latest attempt is a simple electrical device through which an audience member views the screen. In the device, a very light, thin aluminum plate spins continually at a high rate. The screen appears to vanish, while the characters move forward through the air to within close range."

Scientific American, Vol. 128, No. 1; January 1923

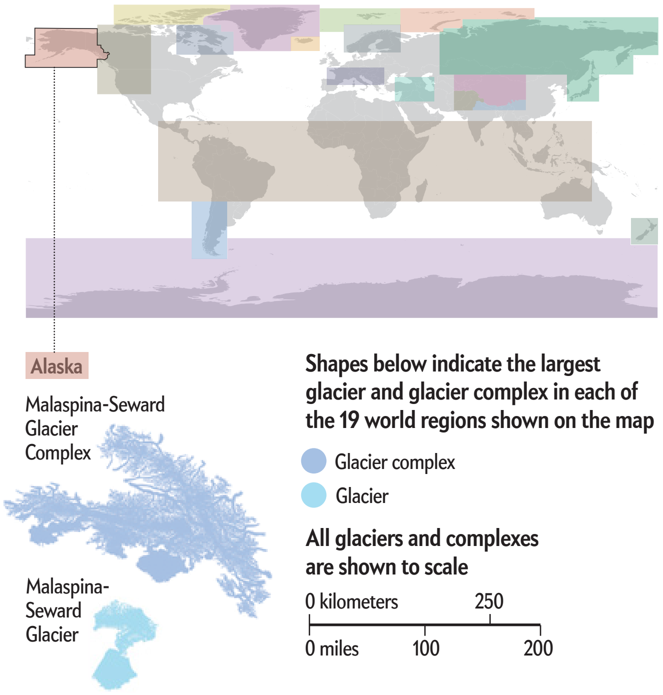
Text by Theo Nicitopoulos | Graphic by Amanda Montañez

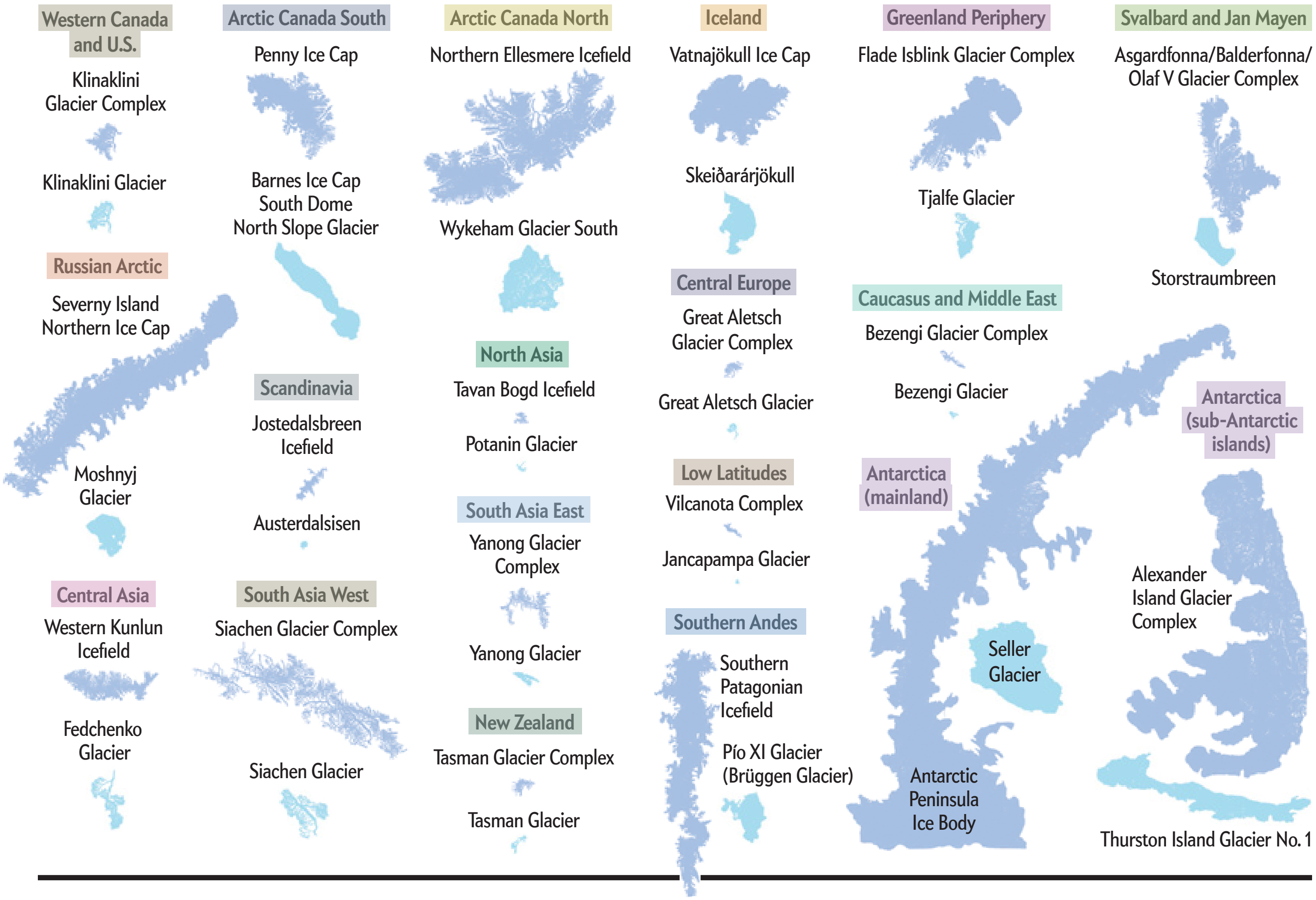
World's Largest Glaciers

A new list highlights Earth's grandest flows of ice

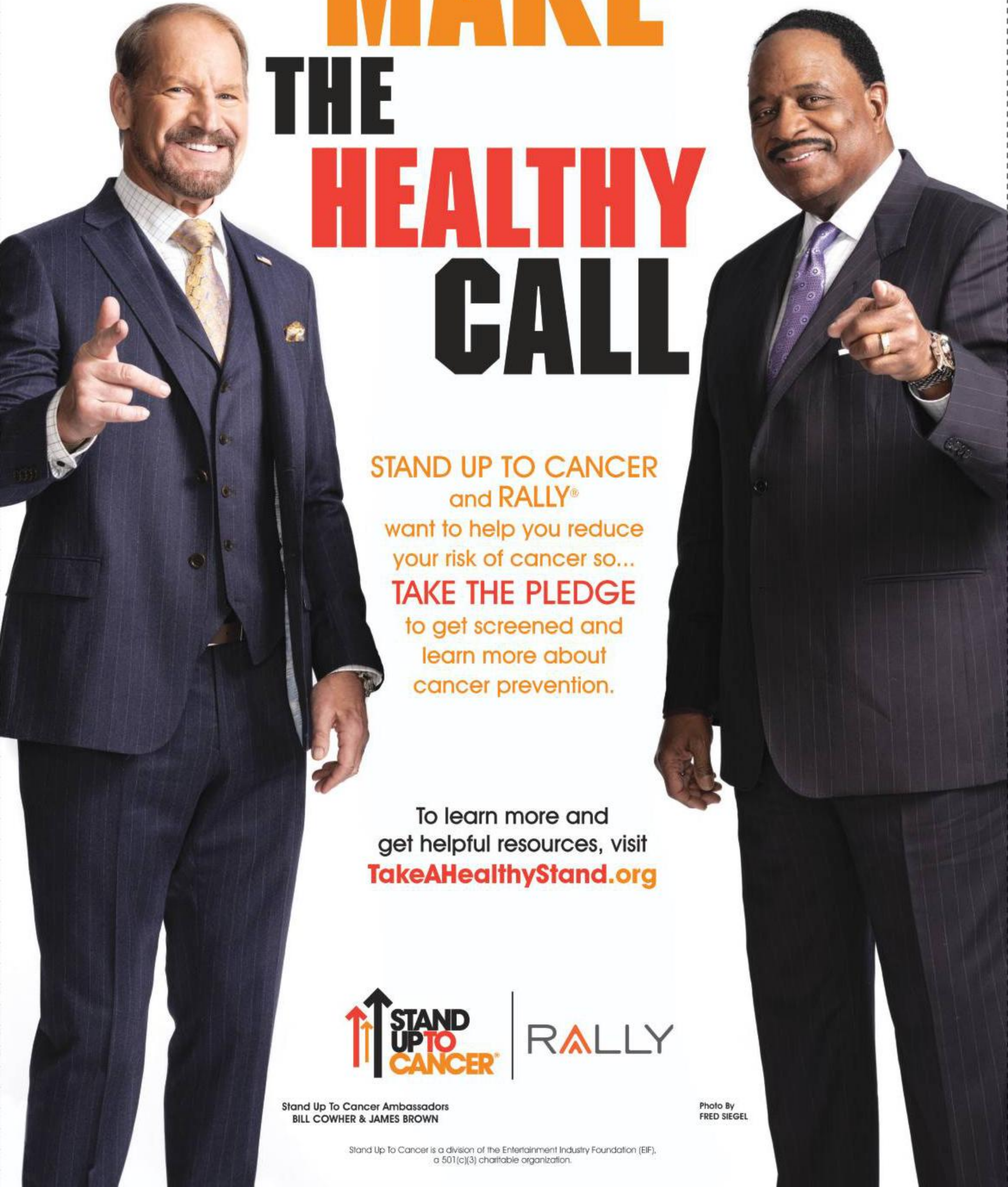
Scientists recently created the first systematic ranking of Earth's largest glaciers. They started by comparing inconsistent databases to select the forms that best fit the definition of a glacier—a long-lasting, flowing mass of ice. Determining the borders of individual glaciers, however, is challenging. Ice caps, for example, move in multiple directions, so more than one glacier may be part of a single source. "Flow divides can be difficult to calculate," says co-author Bruce Raup of the U.S. National Snow and Ice Data Center (NSIDC).

At lower elevations, glaciers can converge, making it unclear whether they count as one or more bodies. Despite the challenges, the results tabulate more than 200,000 glaciers and glacier complexes (glaciers that share a common border). Seller Glacier and the Antarctic Peninsula Ice Body top the list, respectively. "The more accurately we can map glacier outlines, the better we can track their melting due to climate change," says lead author Ann Windnagel of the NSIDC.


Alaska
Malaspina-Seward Glacier Complex
Malaspina-Seward Glacier
Shapes below indicate the largest glacier and glacier complex in each of the 19 world regions shown on the map
Glacier complex
Glacier
All glaciers and complexes are shown to scale
0 kilometers
250
0 miles
100
200


Western Canada and U.S.
Klinaklini Glacier Complex
Klinaklini Glacier
Arctic Canada South
Penny Ice Cap
Barnes Ice Cap South Dome North Slope Glacier
Arctic Canada North
Northern Ellesmere Icefield
Wykeham Glacier South
Iceland
Vatnajökull Ice Cap
Skeiðarárjökull
Greenland Periphery
Flade Isblink Glacier Complex
Tjalfe Glacier
Svalbard and Jan Mayen
Asgardfonna/Balderfonna/Olaf V Glacier Complex
Storstraumbreen
Russian Arctic
Severny Island Northern Ice Cap
Moshnyj Glacier
Scandinavia
Jostedalsbreen Icefield
Austerdalsisen
North Asia
Tavan Bogd Icefield
Potanin Glacier
Central Europe
Great Aletsch Glacier Complex
Great Aletsch Glacier
Caucasus and Middle East
Bezengi Glacier Complex
Bezengi Glacier
Central Asia
Western Kunlun Icefield
Fedchenko Glacier
South Asia West
Siachen Glacier Complex
Siachen Glacier
South Asia East
Yanong Glacier Complex
Yanong Glacier
New Zealand
Tasman Glacier Complex
Tasman Glacier
Low Latitudes
Vilcanota Complex
Jancapampa Glacier
Southern Andes
Southern Patagonian Icefield
Pío XI Glacier (Brüggen Glacier)
Antarctica (mainland)
Seller Glacier
Antarctic Peninsula Ice Body
Antarctica (sub-Antarctic islands)
Alexander Island Glacier Complex
Thurston Island Glacier No. 1

Source: "Which Glaciers Are the Largest in the World?" by Ann Windnagel et al., in *Journal of Glaciology;* 2022 *(glacier shapes and map reference)*



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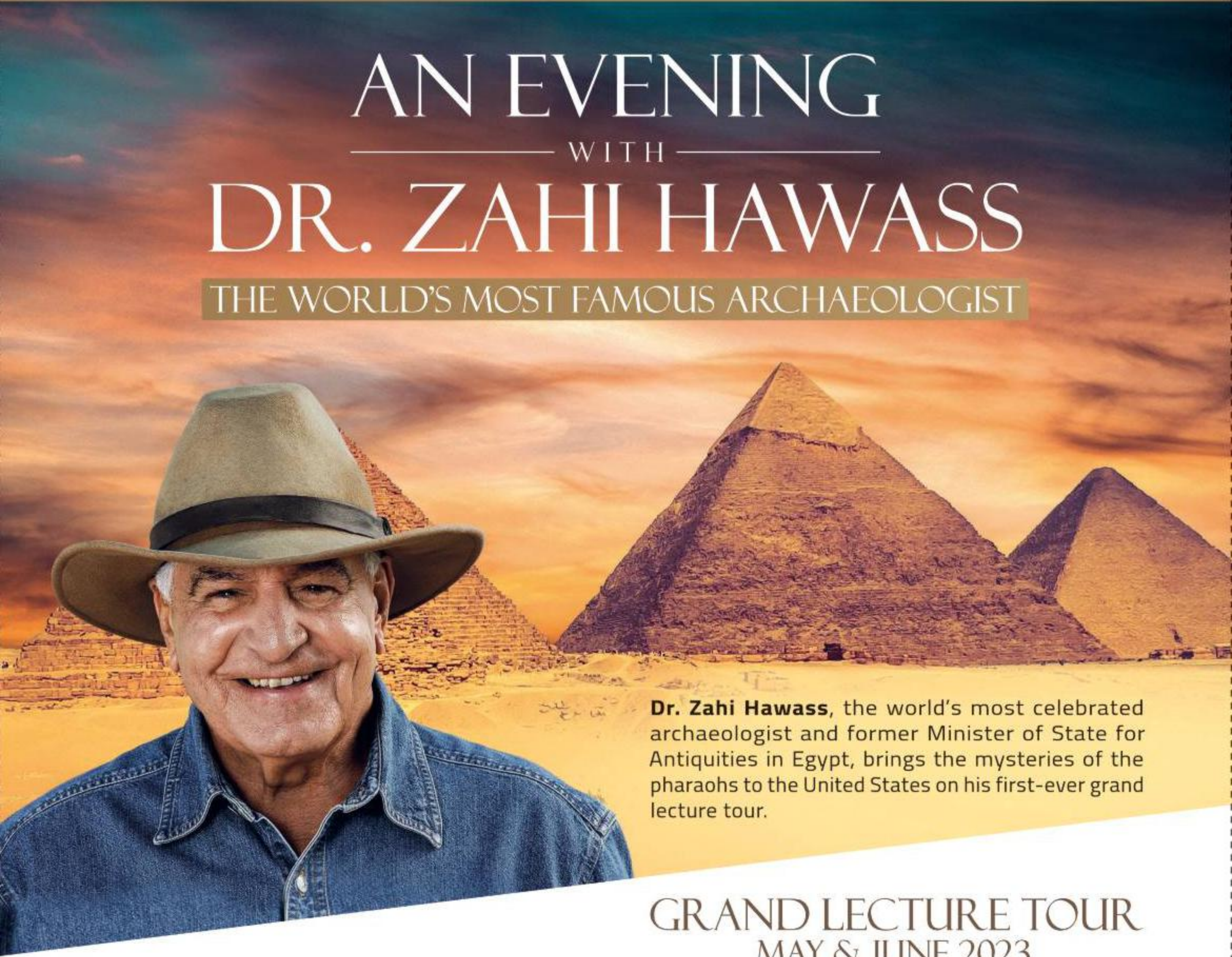
SECRETS OF ANCIENT EGYPT – NEW DISCOVERIES



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